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UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Attorney Docket No.

665P01US

Total Pages

05

First Named Inventor or Application Identifier

Jia XU

Express Mail Label No.

APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

1. ☒ Fee Transmittal Form
(Submit an original, and a duplicate for fee processing)
2. ☒ Specification [Total Pages 185]
(preferred arrangement set forth below)
 - Descriptive title of the Invention
 - Cross References to Related Applications
 - Statement Regarding Fed sponsored R & D
 - Reference to Microfiche Appendix
 - Background of the Invention
 - Brief Summary of the Invention
 - Brief Description of the Drawings (if filed)
 - Detailed Description
 - Claim(s)
 - Abstract of the Disclosure
3. ☒ Drawing(s) (35 USC 113) [Total Sheets 15]
4. Oath or Declaration [Total Pages 2]
 - a. ☒ Newly executed (original or copy)
 - b. ☐ Copy from a prior application (37 CFR 1.63(d))
(for continuation/divisional with Box 17 completed)
[Note Box 5 below]
 - i. ☐ DELETION OF INVENTOR(S)
Signed statement attached deleting inventor(s) named in the prior application, see 37 CFR 1.63(d)(2) and 1.33(b).
5. ☐ Incorporation By Reference (useable if Box 4b is checked)
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.

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6. ☐ Microfiche Computer Program (Appendix)
7. Nucleotide and/or Amino Acid Sequence Submission
(if applicable, all necessary)
 - a. ☐ Computer Readable Copy
 - b. ☐ Paper Copy (identical to computer copy)
 - c. ☐ Statement verifying identity of above copies

ACCOMPANYING APPLICATION PARTS

8. ☐ Assignment Papers (cover sheet & document(s))
9. ☐ 37 CFR 3.73(b) Statement ☐ Power of Attorney
(when there is an assignee)
10. ☐ English Translation Document (if applicable)
11. ☐ Information Disclosure Statement (IDS)/PTO-1449 ☐ Copies of IDS Citations
12. ☐ Preliminary Amendment
13. ☒ Return Receipt Postcard (MPEP 503)
(Should be specifically itemized)
14. ☒ Small Entity ☐ Statement filed in prior application,
Statement(s) ☐ Status still proper and desired
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17. If a CONTINUING APPLICATION, check appropriate box and supply the requisite information:

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	TOTAL CLAIMS (37 CFR 1.16(c))	57 -20 =	37	x \$ 18 =	\$ 666.00
	INDEPENDENT CLAIMS (37 CFR 1.16(b))	6 -3 =	3	x \$ 78 =	234.00
	MULTIPLE DEPENDENT CLAIMS (if applicable) (37 CFR 1.16(d))			+ \$ 0 =	0
				BASIC FEE (37 CFR 1.16(a))	\$760.00
				Total of above Calculations =	1660.00
	Reduction by 50% for filing by small entity (Note 37 CFR 1.9, 1.27, 1.28).				830.00
				TOTAL =	\$830.00

6. Small entity status:

- a. ☒ A small entity statement is enclosed.
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11. SIGNATURE OF APPLICANT, ATTORNEY, OR AGENT REQUIRED

NAME	Robert G. Hendry 22927
SIGNATURE	<i>Robert G Hendry</i>
DATE	June 18, 1999

Applicant or Patentee: Jia Xu Attorney's 665P01US
Serial or Patent No.: unknown as yet Docket No.:
Filed or Issued: on even date herewith
For: A method of Scheduling Executions of Periodic and Asynchronous
Real-Time Processes Having Hard or Soft Deadlines

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY
STATUS (37 CFR 1.9 (f) and 1.27 (b)) — INDEPENDENT INVENTOR

As a below named inventor, I hereby declare that I qualify as an independent inventor as defined in 37 CFR 1.9 (c) for purposes of paying reduced fees under section 41 (a) and (b) of Title 35, United States Code, to the Patent and Trademark Office with regard to the invention entitled _____ described in

☒ the specification filed herewith
☐ application serial no. _____, filed _____
☐ patent no. _____, issued _____

I have not assigned, granted, conveyed or licensed and am under no obligation under contract or law to assign, grant, convey or license, any rights in the invention to any person who could not be classified as an independent inventor under 37 CFR 1.9 (c) if that person had made the invention, or to any concern which would not qualify as a small business concern under 37 CFR 1.9 (d) or a nonprofit organization under 37 CFR 1.9 (e).

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I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28 (b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

Jia Xu
NAME OF INVENTOR NAME OF INVENTOR NAME OF INVENTOR
[Signature] [Signature] [Signature]
Signature of Inventor Signature of Inventor Signature of Inventor
June 14, 1999 _____
Date Date Date

ABSTRACT

A system and methods for scheduling execution of various types of processes. Using information gathered relating to the different processes, pre-run-time scheduling is integrated of run-time scheduling to guarantee that the executions of the processes will satisfy all the specified relations and constraints. Whenever a new set of processes arrives in the system, the system schedules their execution in two phases: a pre-run-time (off-line) phase performed by a pre-run-time scheduler, and a run-time scheduler (on-line) phase performed by a run-time scheduler.

067230-0693250

A METHOD OF SCHEDULING EXECUTIONS OF PERIODIC AND
ASYNCHRONOUS REAL-TIME PROCESSES HAVING HARD OR SOFT
DEADLINES

5 FIELD OF THE INVENTION

 This invention relates to the field of
scheduling methods such as scheduling of processes
carried out by computer or other systems, and in
particular to improved methods of scheduling execution
10 of various types of processes.

BACKGROUND TO THE INVENTION

 In operation of a computer system, executions of
certain periodically or asynchronously occurring real-
time processes must be guaranteed to be completed before
15 specified deadlines, and in addition satisfying various
constraints and dependencies, such as release times,
offsets, precedence relations, and exclusion relations.

 Embedded, real-time systems with high assurance
requirements often must execute many different types of
20 processes with complex timing and other constraints.
Some of the processes may be periodic and some of them
may be asynchronous. Some of the processes may have
hard deadlines and some of them may have soft deadlines.
For some of the processes, especially the hard real-time
25 processes, complete knowledge about their
characteristics can and must be acquired before run-
time. For other processes, a prior knowledge of their
worst case computation time and their data requirements
may not be known.

30 Some processes may have complex constraints and
dependencies between them. For example, a process may
need to input data that are produced by other processes.
In this case, a process may not be able to start before
those other processes are completed. Such constraints
35 are referred to herein as precedence relations.

Exclusion relations may exist between processes when some processes must prevent simultaneous access to shared resources such as data and I/O devices by other processes. For some periodic processes, they may not be
5 able to start immediately at the beginning of their periods. In this case, those processes have release time constraints. For some periodic processes, the beginning of their first period may not start immediately from time zero, that is, the
10 system start time. In this case, those processes have offset constraints.

Examples of such systems include plant control systems, aviation control systems, air traffic control systems, satellite control systems, communication
15 systems, multimedia systems, on-line financial service systems, various embedded systems such as for automotive applications, etc.

Previous systems and methods related to scheduling executions of real-time processes can be
20 broadly divided into two categories:
(a) systems and methods in which determination of the execution schedule of all the processes is done entirely at run-time (on-line); and
(b) systems and methods in which determination of the
25 execution schedule of the majority of the processes is done before run-time (off-line).

The vast majority of systems and methods related to scheduling executions of real-time processes belong to the first category above. The article "Scheduling
30 Algorithms For Multiprogramming in a Hard-Real-Time Environment", by C. L. Liu, and J. W. Layland, J. ACM,

20, 46 - 61, 1973 is the best known representative of the priority scheduling approach. It assumes that all processes are periodic, and that the major characteristics of the processes are known before run-time, that is, the worst case execution times and period are known in advance. Fixed priorities are assigned to processes according to their periods; the shorter the period, the higher the priority. At any time, the process with the highest priority among all processes ready to run, is assigned the processor.

A schedulability analysis is performed before run-time based on the known process characteristics. If certain equations are satisfied, the actual scheduling is performed during run-time, and it can be assumed that all the deadlines will be met at run-time.

The article "Priority Ceiling Protocols: An Approach to Real-Time Synchronization", by L. Sha, R. Rajkumar, and J. P. Lehoczky IEEE Trans. On Computers", 39, 1175 - 1185, 1990, makes the same assumptions as the Liu et al article, except that in addition, processes may have critical sections guarded by semaphores, and a protocol is provided for handling them. Similar to Rate Monotonic Scheduling, a schedulability analysis is performed before run-time based on the known process characteristics; if certain equations are satisfied, the actual scheduling is performed during run-time, and it can be assumed that all the deadlines will be met at run-time.

Variations on the above basic scheme have been proposed, as surveyed by C. J. Fidge in the article "Real-Time Schedulability Tests For Preemptive

66F230-0659E60
Multitasking", published in Real-Time Systems, vol 14,
pp. 61-93, January 1998.

Commercial real-time operating systems perform
all scheduling activities at run-time, during which at
5 each point in time, the process with the highest
priority is selected for execution.

Systems and methods that perform all scheduling
activities at run-time, have the following
disadvantages:

- 10 (a) High run-time overhead due to scheduling and context
switching;
- (b) Difficulty in analyzing and predicting the run-time
behavior of the system;
- (c) Difficulty in handling various application
- 15 constraints and process dependencies;
- (d) Low processor utilization.

High run-time overhead is partly due to the fact
that embedded, real-time applications are becoming more
and more complex, with an ever increasing number of
20 processes and additional constraints and dependencies
between processes. The amount of run-time resources
consumed by the scheduler in order
to compute the schedule, grows very rapidly as the
number of processes and constraints increase. The
25 scheduler often needs to perform many time consuming
process management functions, such as suspending and
activating processes, manipulating process queues, etc.
In addition, since the priority scheduler does not know
the schedule before run-time, it has to assume the worst
30 case and save/restore complete contexts each time a
process is preempted by another process.

Performing all the scheduling at run-time requires the use of complex run-time mechanisms in order to achieve process synchronization and prevent simultaneous access to shared resources. The run-time behavior of the scheduler can be very difficult to analyze and predict accurately.

For example, in one published study, fixed priority scheduling was implemented using priority queues, where tasks are moved between queues by a scheduler that was released at regular intervals by a timer interrupt. It was observed that because the clock interrupt handler had a priority greater than any application task, even a high priority task could suffer long delays while lower priority tasks are moved from one queue to another. Accurately predicting the scheduler overhead proved to be a very complicated task, and the estimated scheduler overhead was substantial, even though it was assumed that the system had a total of only 20 tasks, tasks did not have critical sections, and priorities are not to change. Such difficulties would be many times greater if there existed additional complex application constraints that would have to be satisfied by the synchronization mechanism at run-time.

The original schedulability analysis given in the aforementioned paper describing the PCP protocol by Sha et. al. above, assumed that all tasks are independent tasks, that there are no precedence relations, that their release times are equal to the beginning of their periods, and all periods have a common start time. It is difficult to extend the schedulability analysis for

priority scheduling to take into account application constraints that frequently exist in real-time applications, such as precedence constraints, release times that are not equal to the beginning of their

5 periods, offsets, low jitter requirements (limits on the variation in time a computed result is output to the external environment from cycle to cycle), etc. Despite considerable effort spanning more than a decade to extend

10 the original PCP protocol to handle additional constraints, not much has been accomplished to this end, as evidenced by the absence of methods that can satisfactorily deal with such constraints in the survey by Fidge mentioned above.

15 Additional application constraints increase the computational complexity of scheduling problems, which already have high computational complexity whenever processes contain critical sections. When all the scheduling is performed at run-time, the scheduler does

20 not have enough time to find solutions for complex problems. Most systems and methods that perform all scheduling at run-time, schedule processes according to process priorities assigned by the user. However, additional application constraints are most likely to

25 conflict with the user assigned priorities. It is not generally possible to map the many different execution orderings of processes that are required by the different application constraints in a large complex system onto a rigid hierarchy of priorities.

30 It has been suggested that higher priorities be assigned to processes with: shorter periods, higher

criticality, low jitter requirements, precedence constraints, etc. Consequently, the system designer is faced with the impossible task of trying to simultaneously satisfy many different application

5 constraints with one rigid hierarchy of priorities. Because of the inherent constraints built into the fixed priority scheduling model, (e.g. fixed priorities) and because scheduling is performed at run-time, attempts to take into account additional constraints

10 typically result in suggestions that either are only applicable to a few very special cases, or make drastically simplifying assumptions, which significantly reduce schedulability, or are extremely complicated, making the run-time behavior of the system very

15 difficult to analyze and predict.

In general, systems and methods that perform all scheduling activities at run-time achieve lower processor utilization than systems and methods that schedule processes before run-time. This is largely due

20 to the fact that when all scheduling activities are performed at run-time, the scheduler does not have enough time to find good solutions to complex scheduling problems, and can only afford to use crude, suboptimal methods that do not take into account all the available

25 information.

Systems that use priority scheduling methods have a much smaller chance of satisfying timing constraints, because priority-driven methods are only capable of producing a very limited subset of the

30 possible schedules for a given set of processes. This severely restricts the capability of priority-driven

systems and methods to satisfy timing and resource sharing constraints at run-time.

In general, the smaller the set of schedules that can be produced by a scheduling system or method, the smaller the chances are of finding a feasible schedule, and, the lower the level of processor utilization that can be achieved. With systems that use optimal methods that compute the schedule off-line, it is possible to achieve higher levels of resource utilization than those achievable by priority-driven systems. Hence, using priority-driven systems may increase the cost of the system to non-competitive levels.

When processes are scheduled at run-time, the scheduling strategy must avoid deadlocks. In general, deadlock avoidance at run-time requires that the run-time synchronization mechanism be conservative, resulting in situations where a process is blocked by the run-time synchronization mechanism, even though it could have proceeded without causing deadlock. This reduces further the level of processor utilization.

In contrast to conventional approaches where most of the processes are scheduled at run-time, with pre-run-time scheduling the schedule for most of the processes is computed off-line; this approach requires that the major characteristics of the processes in the system be known, or bounded, in advance. It is known that it is possible to use pre-run-time scheduling to schedule periodic processes. This consists of computing off-line a schedule for the entire set of periodic

processes occurring within a time period that is equal to the least common multiple of the periods of the given set of processes, then at run-time executing the periodic processes in accordance with the previously
5 computed schedule.

In pre-run-time scheduling, several alternative schedules may be computed off-line for a given time period, each such schedule corresponding to a different "mode" of operation. A small run-time scheduler can be
10 used to select among the alternative schedules in response to external or internal events. This small run-time scheduler can also be used to allocate resources for asynchronous processes that have not been converted into periodic processes.

15 It is possible to translate an asynchronous process into an equivalent periodic process, if the minimum time between two consecutive requests is known in advance, and the deadline is not too short. Thus it is also possible to schedule such asynchronous processes
20 using pre-run-time scheduling See "The Design of Real-Time Programming Systems Based On Process Models", Proc. 1984 IEEE Real-time systems Symposium, 5-17, 1984.

Systems and methods that perform scheduling before run-time, have the following advantages:

- 25 (a) ability to effectively handle complex constraints and dependencies;
(b) lower run-time overhead;
(c) higher processor utilization; and
(d) ease of predicting the system's behaviour.

30 In the majority of real-time applications, the bulk of the processing is performed by periodic

processes for which the major characteristics of the processes, including offsets, release times, worst-case execution times, deadlines, precedence and exclusion relations, and any other constraints, are known before
5 run-time. For asynchronous processes, generally their worst-case computation times, deadlines, and the minimum time between two consecutive requests (interarrival times) are known in advance. Asynchronous processes normally are few in number, and often can be converted
10 into new periodic processes that can be used to service the corresponding asynchronous process requests in a manner similar to polling. Thus it is not only possible, but highly desirable to schedule all the periodic processes, including the new periodic processes
15 that are converted from some of the asynchronous processes, before run-time, rather than scheduling them at run-time.

For the processes whose characteristics are known before run-time, such as periodic processes, one
20 may realize important advantages if the schedule is computed before run-time, instead of waiting until run-time to schedule them. This is because when scheduling is done before run-time, there is almost no limit on the running time of the scheduler, optimal scheduling
25 methods can be used to maximize the possibility of finding a feasible schedule for the set of processes to be scheduled and to handle complex constraints and dependencies. In contrast, when processes are scheduled at run-time, the time available to the scheduler is very
30 limited. This limits the ability of the scheduler to

find a feasible schedule and to take into account the different types of constraints and knowledge about the system processes. Once the schedule for the periodic processes has been defined before run-time, the run-time scheduler can also use this information to schedule asynchronous processes more efficiently.

Other reasons for performing scheduling before run-time include: this greatly reduces the run-time resource requirements needed for scheduling and context switching. With pre-run-time scheduling, it is possible to avoid using sophisticated run-time synchronization mechanisms by directly defining precedence relations and exclusion relations on pairs of process segments to achieve process synchronization and prevent simultaneous access to shared resources. Because the schedule is known in advance, automatic code optimization is possible; one can determine in advance the minimum amount of information that needs to be saved and restored, and one can switch processor execution from one process to another process through very simple mechanisms such as procedure calls, or simply by concatenating code when no context needs to be saved or restored, which greatly reduces the amount of run-time overhead.

When the use of sophisticated run-time synchronization mechanisms is avoided, the benefits are multi-fold: not only is the amount of run-time overhead reduced, but it is also much easier to analyze and predict the run-time behavior of the system. Compared with the complex schedulability analysis required when

run-time synchronization mechanisms are used, it is much more straightforward to verify that all processes will meet their deadlines and that all the additional application constraints will be satisfied in an off-line
5 computed schedule.

In recent years, there has been an increased interest in systems and methods for the purpose of automating the process of pre-run-time scheduling, as described in the article by S.R. Faulk and D.L. Parnas
10 "On Synchronization in Hard-Real-time Systems", Commun. ACM vol 31, pp.274-287, March, 1988. Cyclic executives, a form of pre-run-time scheduling, have been used in safety critical systems, e.g. as described by G.D. Carlow in the article "Architecture of the Space Shuttle
15 Primary Avionics Software System", Commun. ACM, Sept. 1984. However, in the past, cyclic executives have mainly been constructed by hand, and are difficult to construct and maintain. In the aforementioned article by A.K. Mok, a technique for transforming an asynchronous
20 process into an equivalent periodic process was introduced. Methods for solving the problem of scheduling processes with release times, deadlines, exclusion and precedence relations are given in the article by J.Xu and D.Parnas in the articles "Scheduling
25 Processes with Release Times, Deadlines, Precedence and Exclusion Relations", IEEE Trans. on Software Engineering, vol 16, pp 360-369, Mar. 1990, by J.Xu and D.L. Parnas in "Pre-run-time Scheduling of Processes with Exclusion Relations on Nested or Overlapping
30 Critical Sections", Proc. Eleventh Annual IEEE International Phoenix Conference on Computers and

Communications, IPCCC-92, Scottsdale, Arizona, April 1-3, 1992, and by J.Xu and D.L. Parnas in "On Satisfying Timing Constraints in Hard-Real-Time Systems", IEEE Trans. on Software Engineering, vol 19, pp1-17, Jan.

5 1993, which are incorporated herein by reference.

However, until now, unsolved problems have been main obstacles to fully automating the process of constructing scheduling systems that combine the pre-run-time scheduling of periodic processes with the run-time scheduling of asynchronous processes, as follows:

(1) Previously there did not exist any system or method that integrates the run-time scheduling of asynchronous processes with the pre-run-time scheduling of periodic processes, that could effectively satisfy exclusion relations, precedence relations, offsets and release times constraints between the periodic processes, as well as any exclusion relation between a periodic process and an asynchronous process, and any exclusion relation between two asynchronous processes, while making efficient use of available processor capacity, and maximizing the chances of satisfying all the timing constraints.

Previous systems and methods for scheduling periodic processes and asynchronous processes, either perform all the scheduling activities at run-time, or assume that any process can be preempted by any other process at any time (no exclusion relations can be enforced, so one cannot prevent certain data inconsistencies that are caused by more than one process simultaneously accessing shared data), or assume that all aperiodic processes have soft deadlines, or assume

processor capacity. For example, in cyclic executives, each periodic application task is required to complete within a fixed size frame, which is of the same size for all periodic application tasks. Such arbitrary

5 constraints seriously restrict the system's ability to meet complex timing constraints.

(3) Previously there did not exist any system or method for systematically determining which asynchronous processes should be converted into new periodic
10 processes, and which asynchronous processes should remain asynchronous, based on whether the ratio of the processor capacity that needs to be reserved for the new periodic process, to the processor capacity that needs to be reserved for the asynchronous process if
15 unconverted, exceeds a specified threshold.

Another embodiment of the present invention provides a system and methods for systematically adjusting the period lengths of periodic processes, such that the adjusted period lengths are sufficiently close
20 to the original period lengths, to satisfy the processor utilization level required by the application, and maximize the chances of finding a feasible schedule, while at the same time ensuring that the adjusted period lengths are as closely harmonically related to each
25 other (having a smaller LCM value) as possible, in order to reduce the schedule length and the number of instances of new processes, and reduce storage requirements and system overhead.

There are certain asynchronous processes that
30 cannot be converted into periodic processes at all, or

if converted, may take up far too much processor capacity compared with allowing them to remain asynchronous. For example, an asynchronous process with a very short deadline, a short worst-case execution
5 time, and with long interarrival times, could require that a overly high proportion, sometimes even exceeding one hundred percent, of the processor's capacity be reserved for that one single process if that process is converted into a periodic process for which it is
10 guaranteed to meet it's deadline. But that same process, may require far less processor capacity be reserved for it, if it was not converted into a periodic process, and scheduled for execution at run-time as soon as it arrives in the system.

15 Previous systems and methods either indiscriminately schedule every asynchronous process at run-time as soon as it arrives in the system, or indiscriminately try to convert every asynchronous process into a periodic process; or rely on ad hoc rules
20 of thumb.

(4) Previously there did not exist any system or method for systematically converting a given set of asynchronous processes into a set of new periodic processes that could make the most efficient use of
25 available processor capacity, and maximize the chances of satisfying all the timing constraints.

In the aforementioned article by A.K. Mok, a technique for converting one single asynchronous process into a periodic process was described. However, the
30 technique described in the Mok article did not consider the case of non-zero offsets, that is, non-zero

intervals between time 0, that is, the system start time, and the beginning of their first periods. If only zero offsets are allowed, the chances of satisfying all the given timing constraints is decreased considerably.

- 5 Furthermore, the described technique only deals with one process. When more than one process must be converted into periodic processes, the new periodic processes may have timing conflicts with each other and with the original set of asynchronous and periodic processes.
- 10 For example, a direct application of the above technique might result in more than one periodic process each having a release time of zero and a deadline equal to the computation time.

- Previous systems and methods use ad hoc methods
- 15 that do not make the most efficient use of available processor capacity. For example, in cyclic executives, each periodic application task is required to complete within a fixed size frame, which is of the same size for all periodic application tasks. Such arbitrary
- 20 constraints seriously restrict the system's ability to meet complex timing constraints.

SUMMARY OF THE INVENTION

- An embodiment of the present invention provides a system and method in which pre-run-time scheduling
- 25 techniques are combined with run-time scheduling techniques, where pre-run-time scheduling is used for scheduling the executions of periodic processes, including new periodic processes converted from a subset of the asynchronous processes, in order to satisfy
- 30 complex relations and constraints such as exclusion relations, precedence relations, and offset constraints,

release time constraints defined on the periodic processes, and any exclusion relation between a periodic process and an asynchronous process, and any exclusion relation between two asynchronous processes, and

5 deadline constraints of all periodic processes, while run-time scheduling is used to schedule a subset of the asynchronous processes that would have consumed too much processor capacity if converted into periodic processes, so that efficient use is made of available processor

10 capacity, and the chances of satisfying all the timing constraints of all processes is increased as much as possible.

In accordance with another embodiment, a pre-run-time scheduler may use existing methods that

15 statically schedules a set of processes (including manual methods to satisfy any special requirements if necessary), to construct a feasible pre-run-time schedule in which processor capacity is reserved in the form of time slots in the pre-run-time schedule for each

20 periodic process. The time slot for each periodic process also includes "room" for the execution of asynchronous processes that have less latitude than that periodic process in meeting their respective deadlines, to allow such asynchronous processes to preempt the

25 execution of that periodic process at run-time. The pre-run-time scheduler adjusts the lengths of the periods using specified parameters which achieve a suitable balance between the utilization level and the length of the pre-run-time schedule. The pre-run-time

30 scheduler is able to schedule periodic processes that have offsets, i.e., intervals between the

start of a periodic process' first period and time zero, that is, the system's start time, and is able to take advantage of any flexibility in periodic process offsets to increase schedulability. The pre-run-time scheduler
5 thereby is able to guarantee that every periodic process will always be able to meet its deadline, while providing good response times for asynchronous processes, without requiring any change in the methods used in any of the other parts, steps or embodiments of
10 the present invention. The system and methods have the flexibility to employ sophisticated static scheduling methods to satisfy complex relations and constraints, such as exclusion relations, precedence relations, offsets and release times defined on the periodic
15 processes, and also have the flexibility to incorporate and take advantage of any future new static scheduling method for satisfying any additional desired constraints among the most important and numerous type of processes in real-time applications, the periodic processes, while
20 making efficient use of available processor capacity, and increasing as much as possible the chances of satisfying the timing constraints all the processes. Thus the present invention is able to satisfy more complex application constraints and achieve higher
25 chances of satisfying complex application constraints on periodic processes than previous systems and methods.

In accordance with an embodiment of the invention, a run-time scheduler uses the information about the beginning times and end times of the time slots reserved for the execution of periodic processes (including those new periodic processes that were

converted from asynchronous processes) in the pre-run-time schedule, as well as the a priori knowledge of the processes characteristics, to make more informed decisions and satisfy any exclusion relation between a periodic process and an asynchronous process, and any exclusion relation between two asynchronous processes, while making efficient use of available processor capacity, and achieving higher chances of satisfying all the timing constraints of the periodic processes, when scheduling the execution of asynchronous processes. For example, an embodiment of the present invention makes it possible to completely avoid blocking of a periodic process with a shorter deadline by an asynchronous process with a longer deadline, thus achieving higher schedulability of periodic processes than previous systems and methods that schedule all processes at run-time.

In accordance with another embodiment, a run-time scheduler can use the information about the beginning times and end times of the time slots reserved for the execution of periodic processes (including those new periodic processes that were converted from asynchronous processes) in the pre-run-time schedule, as well as the a priori knowledge of the processes characteristics. A significant portion of the parameters used by the asynchronous process scheduler to make scheduling decisions are known before run-time so it is possible to pre-compute major portions of the conditions that are used for decision making. Hence the amount of computation that needs to be performed for scheduling purposes at run-time can be minimized, while

making efficient use of available processor capacity,
and increasing as much as possible the chances of
satisfying all the timing constraints of the
asynchronous processes. For example, an embodiment of
5 the present invention makes it possible to create before
run-time, a table of "safe starting time intervals" for
each asynchronous process, and achieve low run-time
overhead than previous systems and methods by allowing
the asynchronous processes to be scheduled by simple
10 table lookup.

In accordance with another embodiment of the
invention, bounds on the worst-case response times of
asynchronous processes are computed, that are more
accurate (tighter) than that achievable with previous
15 systems and methods, by using a simulation procedure
that takes into account the beginning times and end
times of the time slots reserved for the execution of
periodic processes including those new periodic
processes that were converted from asynchronous
20 processes) in the pre-run-time schedule, as well as the
a priori knowledge of the processes characteristics,
when simulating all possible worst-case scenarios of the
executions of each asynchronous process.

In accordance with another embodiment, a system
25 and methods can schedule the executions of both periodic
and asynchronous real-time processes with hard or soft
deadlines, with different a priori knowledge of the
process characteristics, and with constraints and
dependencies, such as offsets, release times, precedence
30 relations, and exclusion relations, in real-time on a
single processor. This exploits to a maximum extent any

knowledge about processes' characteristics that are available to the scheduler both before run-time and during run-time, so that processor capacity is used to satisfy the constraints

- 5 and dependencies of periodic and asynchronous processes with hard deadline process as a first priority. Then any remaining processor capacity is used to guarantee that processes with soft deadlines and known characteristics will also be completed before pre-
- 10 determined time limits as a second priority. Then any remaining processor capacity is used to execute any asynchronous process with unknown characteristics on a "best-effort" basis.

- In accordance with another embodiment, a system
- 15 and methods schedule the executions of both periodic and asynchronous real-time processes with hard or soft deadlines, with different a priori knowledge of the process characteristics, and with constraints and
- 20 dependencies, such as offsets, release times, precedence relations, and exclusion relations, in real-time on a single processor. This exploits to a maximum extent any knowledge about processes' characteristics that are available to the scheduler both before run-time and
- 25 during run-time, in order to:
- (a) effectively handle complex application constraints and dependencies between the real-time processes;
 - (b) minimize run-time overhead;
- 30 (c) make the most efficient use of available processor capacity,

- (d) maximize the chances of satisfying all the timing constraints, and
- (e) provide firm and tight response time guarantees for all the processes whose characteristics are known before run-time;
- (f) make it easier to verify that all timing constraints and dependencies will always be satisfied.

Thus the present invention is able to schedule a wider variety of processes with a wider variety of constraints compared with previous systems and methods.

In accordance with another embodiment, which asynchronous processes should be converted into new periodic processes is automatically determined, and which asynchronous processes should remain asynchronous. This is based on whether the ratio of the processor capacity that needs to be reserved for the new periodic process, to the processor capacity that needs to be reserved for the asynchronous process if unconverted, exceeds a user or otherwise determined specified threshold.

An embodiment of the invention systematically converts a given set of asynchronous processes into a set of new periodic processes that could make the most efficient use of available processor capacity, and increase as much as possible the chances of satisfying all the timing constraints.

All of the above can be achieved while the process of constructing scheduling systems that combine pre-run-time scheduling with run-time scheduling of periodic and asynchronous processes is fully automated, while the most efficient use of available processor

capacity is achieved, the chances of satisfying all the timing constraints is increased as much as possible. Thus the present invention can achieve a much higher degree of automation, and substantially reduce the cost of designing the system and of making changes to the systems to meet new requirements, reduce the chances of errors, as compared with previous systems and methods that schedule processes before run-time.

An embodiment of the present invention provides a system and methods for scheduling execution of both periodic and asynchronous real-time processes with hard or soft deadlines, with different a priori knowledge of the process characteristics, such that complex relations and constraints, such as exclusion relations, precedence relations, offset constraints and release time constraints defined on the hard deadline periodic processes, and any exclusion relation between a hard deadline periodic process and a hard deadline asynchronous process, and any exclusion relation between two hard deadline asynchronous processes, and deadline constraints of all hard deadline processes, can be satisfied on a single processor.

An embodiment of the present invention integrates pre-run-time scheduling with run-time scheduling to guarantee that the executions of the processes will satisfy all the specified relations and constraints. Whenever a new set of processes arrives in the system, the system schedules their executions in two phases: a pre-run-time (off-line) phase performed by a pre-run-time scheduler, and a run-time (on-line) phase performed by a run-time scheduler.

In accordance with an embodiment of the invention, in each pre-run-time phase, the pre-run-time scheduler executes five steps, as follows:

In Step 1, the pre-run-time scheduler divides
5 asynchronous processes with hard deadlines and known characteristics, referred to herein as A-h-k processes, into two subsets. One subset of asynchronous processes, referred to herein as A-h-k-p processes, are converted into new periodic processes by the pre-run-time
10 scheduler before run-time. When the pre-run-time scheduler converts an asynchronous process into a new periodic process, it prevents possible timing conflicts with other periodic and asynchronous processes, by reserving enough "room" (time) prior to each new
15 periodic process's deadline, to accommodate the computation times of all the periodic and asynchronous processes that have less latitude in meeting their deadlines, to allow such processes to preempt that new periodic process if possible at run-time. The processes
20 in the other subset of asynchronous processes, referred to herein as A-h-k-a, remain asynchronous and are scheduled by the run-time scheduler at run-time. The pre-run-time scheduler reserves processor capacity for A-h-k-a processes by adding the computation time of each
25 A-h-k-a process to the computation time of every periodic process that has a greater latitude in meeting its deadline than that A-h-k-a process, to allow each A-h-k-a process to preempt the execution of any such periodic process if possible at run-time.

30 Whether each asynchronous process is converted into a new periodic process or not, is determined based

on whether the ratio of the processor capacity that
needs to be reserved for the new periodic process, to
the processor capacity that needs to be reserved for the
asynchronous process if unconverted, exceeds a user or
5 otherwise specified threshold.

In Step 2, the pre-run-time scheduler determines
the schedulability of the set of all periodic processes
with hard deadlines and known characteristics, referred
to herein as P-h-k processes, which also include the new
10 periodic processes converted from A-h-k-p processes. The
pre-run-time scheduler constructs a pre-run-time
schedule in which one or more time slots are reserved
for the execution of every P-h-k process, including
every new P-h-k process converted from an A-h-k-p
15 process. The time slots reserved for each P-h-k process
also include time reserved for the executions of all A-
h-k-a processes that have less latitude in meeting their
deadlines than that P-h-k process, and which may preempt
the execution of that P-h-k process. The pre-run-time
20 scheduler adjusts the lengths of the periods using for
example user or otherwise specified parameters which
control the balance between the utilization level and
the length of the pre-run-time schedule.

The pre-run-time scheduler is able to schedule
25 periodic processes that have offsets, i.e., intervals
between the start of a periodic process' first period
and time zero. The pre-run-time scheduler takes
advantage of any flexibility in periodic process offsets
to increase schedulability. An embodiment of the
30 present invention preferably allows the pre-run-time
scheduler to use existing methods (including manual

methods) which statically schedule set of processes, to
construct the pre-run-time schedule of periodic
processes in Step 2 and in Step 4 (to be described
below), without requiring any change in the methods used
5 in any of the other steps of the present invention.
This allows the system and methods to have the
flexibility to incorporate and take advantage of any
future new static scheduling method for satisfying any
additionally desired constraints among the most
10 important and numerous type of processes in real-time
applications, the periodic processes.

The pre-run-time scheduler includes a function
"adjustperiod" which uses a sorted list of reference
periods to adjust the length of the period of each
15 periodic process. Each reference period is equal to 2^i
 $\times 3^j \times 5^k \times 7^l \times 11^f$, ..., for some integers i, j, k, l, f ,
... where $0 \leq i \leq \exp_2$, $0 \leq j \leq \exp_3$, $0 \leq k \leq \exp_5$, 0
 $\leq l \leq \exp_7$, $0 \leq f \leq \exp_{11}$, ... $\exp_2, \exp_3, \exp_5, \exp_7,$
 \exp_{11} , ..., are the upperbounds on the exponents $i, j, k,$
20 l, f , ..., that are applied to the prime numbers 2, 3, 5,
7, 11, Application dependent parameters are used to
fine tune the exponent upperbounds which control the
balance between the utilization level and the length of
the pre-run-time schedule.

25 In Step 3, the pre-run-time scheduler uses
knowledge about the time slots reserved for the P-h-k
processes in the pre-run-time schedule, to determine,
before run-time, the worst-case response times of all A-
h-k-a processes. The pre-run-time scheduler preferably
30 uses one of two methods, one a formula, the other a
simulation procedure, for determining the worst-case

In Step 5, the pre-run-time scheduler preferably uses knowledge about the time slots reserved for the P-h-k and P-s-k processes in the pre-run-time schedule to determine, before run-time, the worst-case response
5 times of asynchronous processes with soft deadlines and known characteristics, i.e., A-s-k processes.

At the end of the pre-run-time phase, a feasible pre-run-time schedule for all the periodic processes with known characteristics should be constructed, while
10 the worst-case response times of all the asynchronous processes with known characteristics should be determined.

During the run-time phase, a run-time scheduler uses knowledge about the time slots reserved for the
15 periodic processes in the pre-run-time schedule to schedule the executions of all the periodic and asynchronous processes, that is, the P-h-k processes (including every new P-h-k process converted from an A-h-k-p process), P-s-k processes, A-h-k-a processes, A-s-
20 k processes, as well as asynchronous processes with soft deadlines and unknown characteristics (referred to herein as A-s-u processes, in a way that guarantees that every periodic process's execution will complete before the end of that periodic process's time slot in the pre-
25 run-time schedule, and all the asynchronous processes with soft deadlines and known characteristics, are guaranteed to be completed within the worst-case response time pre-determined in Step 4 and Step 5 after their arrival, so that all the constraints and
30 dependencies of all processes with known characteristics will always be satisfied. The run-time scheduler, can

use the information about the beginning times and end times of the time slots reserved for the execution of periodic processes (including those new periodic processes that were converted from asynchronous processes) in the pre-run-time schedule, as well as the a priori knowledge of the processes characteristics, to pre-compute major portions of the conditions that are used for decision making, hence the amount of computation that needs to be performed for scheduling purposes at run-time can be minimized.

For example, the present invention makes it possible to create before run-time, a table of "safe starting time intervals" for each asynchronous process, and achieve lower run-time overhead than previous systems and methods by allowing the asynchronous processes to be scheduled by simple table lookup.

A-s-u processes are scheduled at run-time on a "best-effort" basis using the remaining processor capacity.

The present invention exploits to a maximum extent any knowledge about the characteristics that are available to the system both before run-time and during run-time, in order to:

- (a) effectively handle complex application constraints and dependencies between the real-time processes;
- (b) minimize run-time overhead;
- (c) maximize the chances of being able to guarantee that all the processes with hard deadlines will always meet their deadlines;

(d) provide firm and tight response time guarantees for all the processes whose characteristics are known before run-time; and

(e) make it easier to verify that all timing constraints and dependencies will always be satisfied.

It is believed that as compared with previous systems

and methods that perform all scheduling activities at run-time, for most real-time applications, the present invention is better suited to meeting the above for the following reasons:

(1) In most real-time applications the bulk of the computation is usually performed by periodic processes for which the characteristics are known a priori. Complex constraints and dependencies are normally defined on the periodic processes. In the present invention, all the periodic processes are scheduled before run-time, there is practically no limit on the time that can be used for scheduling the periodic processes. This allows the use of better methods to handle a great variety of application constraints and dependencies, and thus can achieve higher schedulability for the most important and most numerous type of processes in real-time applications.

(2) The run-time overhead required for scheduling and context switching is much smaller than that of the prior art.

(3) The number of asynchronous processes that the run-time scheduler needs to schedule should be small,

as in most real-time applications. In most real-time applications the number of asynchronous processes with hard deadlines is usually small.

5 (4) A significant portion of asynchronous processes can be transformed into periodic processes, if desired by the user, when using the present invention. For those asynchronous processes that are not transformed
10 into periodic processes, their interarrival times are likely to be long.

 (5) Most of the important scheduling decisions have already been determined before run-time. In particular, the relative ordering of all the periodic
15 processes was determined before run-time when the pre-run-time schedule was computed.

 (6) A significant portion of the parameters used by the run-time scheduler to make scheduling decisions for asynchronous processes, are known before run-time,
20 so that major portions of the conditions that are used for decision making can be pre-computed, and the amount of computation that needs to be performed for scheduling asynchronous processes at run-time can be minimized.

 (7) From the pre-run-time schedule, it becomes
25 known in advance exactly which periodic process may preempt which other periodic process at run-time. Thus one can use this information to minimize the amount of context switching.

 (8) Once the pre-run-time schedule has been
30 determined for all the periodic processes, the run-time scheduler can use this knowledge to achieve higher

5 (14) The number of asynchronous processes is reduced, and the ordering of the periodic processes is fixed in the pre-run-time schedule. This significantly reduces the complexity of verifying that the asynchronous processes will meet timing constraints.

In accordance with another embodiment of the invention, a method of scheduling executions of both periodic and asynchronous real-time processes having hard or soft
10 deadlines, comprises automatically generating a pre-run-time schedule comprising mapping from a specified set of periodic process executions to a sequence of time slots on a time axis, each of the time slots having a beginning time and an end time, reserving each one of
15 the time slots for execution of one of the periodic processes, a difference between the end time and the beginning time of each of the time slots being sufficiently long that execution of all of the periodic processes, including satisfaction of predetermined
20 constraints and relations comprising at least one of release time, worst-case computation time, period, deadline, deadline nature, offset and permitted range of offset constraints, and precedence and exclusion relations and criticality levels can be completed
25 between the beginning time and end time of respective time slots, and executing the processes in accordance with the schedule during run-time of the processor.

In accordance with another embodiment, a method for automatically adjusting lengths of periods of a
30 predetermined set of periodic processes, comprises storing and sorting a list of reference periods, setting

the length of the period of each periodic process to the length of the largest reference period that is no larger than an original period of the periodic process to form adjusted periods, and storing the adjusted periods for
5 subsequent use in scheduling executions of the periodic processes.

In accordance with another embodiment, a method of processing a plurality of processes, some of which are periodic and some of which are asynchronous,
10 comprises:

(i) prior to executing the processes on a processor:

(a) determining which asynchronous processes have less flexibility in meeting their deadlines than any of the periodic processes,

15 (b) adding the execution time of each of the less flexible asynchronous processes to the execution time of each of the periodic periodic processes,

(c) scheduling each of the periodic processes into time slots,

20 (ii) and during run-time of the processor:

(d) executing the periodic processes according to the schedule, interrupting any periodic process to execute an of said less flexible asynchronous processes for which a request to execute has been received by the
25 processor,

(e) on receiving a request to execute an asynchronous process which has greater or equal flexibility in meeting their deadlines than any of the periodic processes, scheduling the requesting
30 asynchronous process at a time which will not conflict

with execution and completion of any of the periodic processes, and

(f) executing the scheduled latter asynchronous process at its scheduled time.

5 In accordance with another embodiment, a method of processing a plurality of processes, some of which are periodic and some of which are asynchronous, comprises:

(i) prior to executing the processes:

10 (a) determining which asynchronous processes have less flexibility in meeting their deadlines than any of the periodic processes,

(b) adding the execution time of each of the less flexible asynchronous processes to the execution
15 time of each of the periodic processes,

(c) scheduling each of the periodic processes into time slots,

(d) converting each asynchronous process which has greater or equal flexibility in meeting their
20 deadlines than any of the periodic processes into a new periodic process, and scheduling the new periodic process at a time which will not conflict with execution and completion of any of the other periodic processes,

(ii) and during run-time,

25 (e) executing the periodic and new periodic processes, interrupting any of the periodic and new periodic processes to process any of the less flexible asynchronous processes for which a request to execute may be received at any time.

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In accordance with another embodiment, a method of scheduling execution of processes by a processor comprises:

- (a) scheduling periodic time slots for all periodic processes which time slots each include time for each of the periodic processes and time for all asynchronous processes which have less flexibility in meeting their deadlines than do the periodic processes,
- (b) determining worst case response times of all other processes,
- (c) construct a schedule which includes the periodic time slots and sufficient intervening time to process said all other processes, and
- (d) executing the processes in accordance with the schedule and as said all other processes are required to be processed from time to time.

BRIEF INTRODUCTION TO THE DRAWINGS

A better understanding of the invention may be obtained by reading the detailed description of the invention below, in conjunction with the following drawings, in which:

Figure 1 is a feasibility schedule for an embodiment of the invention,

Figure 2 is a timing diagram of possible run-time execution of certain asynchronous and periodic processes,

Figures 3 and 8 are feasibility schedules for other embodiments of the invention,

Figures 4, 5, 6, 7 and 9 are timing diagrams of possible run-time execution of other asynchronous and periodic processes,

Figures 10, 11 12 and 13 are example timing diagrams of possible run-time execution of various periodic processes,

Figure 14 is another example of a feasibility
5 schedule, Figure 15, 16 and 17 are example timing diagrams of possible run-time execution of various periodic processes,

Figure 18 is another example of a feasibility schedule,

10 Figure 19 is another example of a pre-run-time schedule,

Figures 20A - 20H are timing diagrams used in the explanation of various example cases,

Figure 21 is a timing diagram of a feasible
15 schedule on two processors,

Figures 22 and 23 are timing diagrams of pre-run-time schedulers, on two processors, and

Figures 24 and 24A are block diagrams of systems on which the present invention can be carried out.

20 DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Example embodiments will now be given which illustrate operation and advantages of the present invention as compared with systems and methods that
25 perform all scheduling activities at run-time. It should be noted that existing systems and methods that perform all scheduling activities at run-time are not able to guarantee the schedulability of the set of processes given in these examples. Some of the
30 embodiments will be described in pseudocode, which is a

shorthand form of English understandable to persons skilled in the field of this invention.

Periodic Processes

A periodic process consists of a computation
5 that is executed repeatedly, once in each fixed period of time. A typical use of periodic processes is to read sensor data and update the current state of internal variables and outputs.

A periodic process p can be described by a
10 quintuple $(o_p, r_p, c_p, d_p, prd_p)$, wherein prd_p is the period, c_p is the worse case computation time required by process p , d_p is the deadline, i.e., the duration of the time interval between the beginning of a period and the time by which an execution of process p must be
15 completed in each period, r_p is the release time, i.e., the duration of the time interval between the beginning of a period and the earliest time that an execution of process p can be started in each period, and o_p is the offset, i.e., the duration of the time interval between
20 the beginning of the first period and time 0.

It is assumed that $o_p, r_p, c_p, d_p, prd_p$ as well as any other parameters expressed in time have integer values. A periodic process p can have an infinite number of periodic process executions $\{p_0, p_1, p_2, \dots,$
25 with one process execution for each period. For the i th process execution p_i corresponding to the i th period, p_i 's release time is $R_{pi} = o_p + r_p + prd_p \times (i-1)$; and p_i 's deadline is $D_{pi} = o_p + d_p + prd_p \times (i-1)$. The uppercase letters R and D in R_p and D_p are used herein
30 to denote the release time and deadline respectively of a periodic process execution of some periodic process p .

Reference is made to Figure 11 and Figure 12 for examples of periodic processes. Figure 11 illustrates the periodic process $p_B = o_{pB}, r_{pB}, c_{pB}, d_{pB}, prd_{pB}$ where $r_{pB} = 1, d_{pB} = e, d_{pB} = 4, prd_{pB} = 12$ and $o_{pB} = 0$. Figure 12 illustrates the periodic process $p_D = o_{pD}, r_{pD}, c_{pD}, d_{pD}, prd_{pD}$ where $r_{pD} = 0, c_{pD} = 4, d_{pD} = 4, prd_{pD} = 12$ and $o_{pD} = 7$.

Asynchronous Processes

An example of an asynchronous process is one which consists of a computation that responds to internal or external events. A typical use of an asynchronous process is to respond to operator requests. Although the precise request times for executions of an asynchronous process a are not known in advance, usually the minimum amount of time between two consecutive requests min_a is known in advance. An asynchronous process a can be described by a triple (c_a, d_a, min_a) . c_a is the worse case computation time required by process a . d_a is the deadline, i.e., the duration of the time interval between the time when a request is made for process a and the time by which an execution of process a must be completed. An asynchronous process a can have an infinite number of asynchronous process executions a_0, a_1, a_2, \dots , with one process execution for each asynchronous request. For the i^{th} asynchronous process execution a_i which corresponds to the i^{th} request, if a_i 's request (arrival) time is R_{ai} , then a_i 's deadline is $D_{ai} = R_{ai} + d_a$.

The uppercase letters R and D in R_a and D_a will be used herein to denote the request (arrival) time and

deadline respectively of an asynchronous process execution of some asynchronous process a .

Schedules

If a periodic process p or an asynchronous process a has a computation time of c_p or c_a , then it is assumed that that process execution p_i or a_i is composed of c_p or c_a process execution units. Each processor is associated with a processor time axis starting from 0 and is divided into a sequence of processor time units.

A schedule is a mapping from a possibly infinite set of process execution units to a possibly infinite set of processor time units on one or more processor time axes. The number of processor time units between 0 and the processor time unit that is mapped to by the first unit in a process execution is called the start time of that process execution. The number of time units between 0 and the time unit subsequent to the processor time unit mapped to by the last unit in a process execution is called the completion time of that process execution. A feasible schedule is a schedule in which the start time of every process execution is greater than or equal to that process execution's release time or request time, and its completion time is less than or equal to that process execution's deadline.

Reference is made to Figures 1-9, 14 and 18 are examples of feasible schedules, wherein the horizontal axis is the time axis, and time period segments are separated by vertical lines which represent release times and deadlines, as will be described below.

It should be noted that, in order to avoid use in this specification of an exceedingly large number of

repetitions of use of the word "executions of process" or "executions of process i", these terms have been in many places herein abbreviated to the word "process", or to simply "i". Thus whenever there is a reference to
5 the term "process" as related to a schedule, the term "process" or "process i", or "i" when i is the name of a process should be understood as meaning "process execution" or "the execution of process I".

Process Segments

10 Each process p may consist of a finite sequence of segments
 $p(0), p(1), \dots, p(n(p))$, where $p(0)$ is the first segment and $p(n(p))$ is the last segment in process p. Given the release time r_p , deadline d_p of process p and
15 the computation time of each segment p_i in process p, one can easily compute the release time and deadline for each segment, as described in the aforementioned 1993 article by Xu and Parnas.

Parallel computations can be represented by
20 several
processes, with various types of relations defined between individual segments belonging to different processes, and processes can be executed concurrently; thus requiring each process to be a sequence of segments
25 does not pose any significant restrictions on the amount of parallelism that can be expressed.

Precedence and Exclusion Relations

Various types of relations such as precedence relations and exclusion relations may exist between
30 ordered pairs of processes segments. A process segment i is said to precede another process segment j if j can

only start execution after i has completed its computation. Precedence relations may exist between process segments when some process segments require information that is produced by other process segments.

5 A process segment i is said to exclude another process segment j if no execution of j can occur between the time that i starts its computation and the time that i completes its computation. Exclusion relations may exist between process segments when some process
10 segments must prevent simultaneous access to shared resources such as data and I/O devices by other process segments.

Latitude of a Process

15 The "latitude" of a process x, denoted by L_x , is a user defined measure of the latitude in meeting process x's deadline.

For exemplary purposes, in all the examples given in the description of the present invention, I will assume that
20 for each process x, L_x is set to the following value:

--- for each periodic process p_i , $L_{p_i} = d_{p_i} - r_{p_i}$

--- for each asynchronous process a_i , $L_{a_i} = d_{a_i}$

It should be noted that L_x can be defined differently

25 according to some other criteria, depending on the application.

(For example, for each P-h-k process or P-s-k process p_i , instead of defining $L_{p_i} = d_{p_i} - r_{p_i}$, $L_{p_i} = d_{p_i}$ could be defined, or any other criteria for defining L_{p_i} could be
30 used.

Main Types of Processes

The main types of processes that are considered herein are the following:

- Set P-h-k: Periodic processes with hard deadlines and known characteristics. Each such process
- 5 may consist of one or more segments, with precedence relations defined on them to enforce the proper ordering of segments belonging to the same process. It is assumed that the following characteristics are known for each such process segment before run-time:
- 10 -- period,
 -- worst-case execution time,
 -- release time,
 -- deadline,
 -- the set of data that each segment reads and
- 15 writes,
 -- any exclusion relationships with other process segments,
 -- any precedence relationships with other periodic process segments.
- 20 Set A-h-k: Asynchronous processes with hard deadlines and known characteristics. It is assumed that each such process consists of a single segment and the following are known for each such process before run-time:
- 25 -- deadline,
 -- worst-case execution time,
 -- minimum time between two consecutive requests,
 -- the set of data that the process reads and
- writes,
- 30 -- any exclusion relationships with other process segments.

nothing else is known about each such process before run-time.

In the present invention, as well as in the method described in the 1993 article by Xu and Parnas referred to above, and that can be used in the present invention, It is assumed that the basic scheduling unit is a segment. The terms "segment" and "process will also be considered as having the same meaning.

10 Pre-Run-Time Phase

Step 1: Conversion of A-h-k-p processes

In this step asynchronous processes with hard-deadlines and known characteristics are referred to as A-h-k processes. The A-h-k processes are divided into two subsets. Different methods will be used to reserve processor capacity for the execution of the processes in each of the two subsets.

The processes in one of subsets, called A-h-k-p processes, should be converted into equivalent new periodic processes with hard deadlines. The remaining A-h-k processes are called A-h-k-a processes and processor capacity should be reserved for their execution before run-time.

For each A-h-k-a process, processor capacity in each hard-deadline periodic process should be reserved by the following.

Let S_p be the original set of P-h-k processes;

Let S_A be the original set of A-h-k processes;

Let S_a be the set of A-h-k processes that have not been converted into periodic processes;

Let S_p be the set of new periodic processes that are converted from A-h-k-p processes.

For each $p_i \in (S_p \cup S_p)$, calculate its "adjusted computation time" c_{pi} as follows.

$$5 \quad c_{pi}' = c_{pi} + \text{adjusted capacity}(p_i)$$

The exact adjusted capacity function that is used depends on the application characteristics: for example it may depend on the number of processors that are used, and other factors.

10 In the examples, we will assume that the following simple formula is used:

Adjusted capacity(p_i) =

$$\sum_{a_j \in S_a \wedge L_{a_j} < L_{p_i}} \left\lceil \frac{d_{p_i} - r_{p_i}}{\min_{a_j}} \right\rceil c_{a_j}$$

Above, for each process p_i in S_p (the original set of P-h-k processes) or in S_p (the new periodic processes converted from A-h-k-p processes), for every possible occurrence of any A-h-k-a process a_j between r_{p_i} and d_{p_i} , if $L_{a_j} < L_{p_i}$ then a_j 's computation time is added to p_i 's computation time.

Example 1.

Assume 4 asynchronous processes with hard deadlines and known characteristics (A-h-k processes), and 4 periodic processes with hard deadlines and known characteristics (P-h-k processes) as follows.

$$d_{\text{new}p_i} = c_{a_i} + \text{conversion room}(a_i);$$

The exact conversion room function that is used depends on the application characteristics.

In the following two examples, first assume that the following simple formula is used.

$$\text{Conversion_room}(x_i) =$$

5

$$\begin{aligned} a_0: & c_{a_0} = 2, d_{a_0} = 2, \min_{a_0} = 1,000; \\ a_1: & c_{a_1} = 2, d_{a_1} = 7, \min_{a_1} = 1,000; \\ a_2: & c_{a_2} = 10, d_{a_2} = 239, \min_{a_2} = 1,000; \\ a_9: & c_{a_9} = 10, d_{a_9} = 259, \min_{a_9} = 1,000; \\ p_4: & r_{p_4} = 0, c_{p_4} = 26, d_{p_4} = 200, \text{prd}_{p_4} = 200, o_{p_4} = 0; \\ p_5: & r_{p_5} = 30, c_{p_5} = 16, d_{p_5} = 50, \text{prd}_{p_5} = 200, o_{p_5} = 0; \\ p_6: & r_{p_6} = 0, c_{p_6} = 26, d_{p_6} = 200, \text{prd}_{p_6} = 200, o_{p_6} = 0; \\ p_7: & r_{p_7} = 0, c_{p_7} = 16, d_{p_7} = 200, \text{prd}_{p_7} = 200, o_{p_7} = 0. \end{aligned}$$

The adjusted computation times for p_4, p_5, p_6, p_7 will respectively be:

$$\begin{aligned} c_{p_4}' &= c_{p_4} + c_{a_0} + c_{a_1} = 26 + 2 + 2 = 30; \\ c_{p_5}' &= c_{p_5} + c_{a_0} + c_{a_1} = 16 + 2 + 2 = 20; \\ c_{p_6}' &= c_{p_6} + c_{a_0} + c_{a_1} = 26 + 2 + 2 = 30; \\ c_{p_7}' &= c_{p_7} + c_{a_0} + c_{a_1} = 16 + 2 + 2 = 20. \end{aligned}$$

□

periodic processes. For example, a direct application of the Moka technique could result in more than one periodic process each having a release time of zero and a deadline equal to the computation time.

5 In order to avoid such timing conflicts, in accordance with an embodiment of the present invention a procedure is used for converting a set of asynchronous processes into periodic processes, which also takes into account the possibility
10 of timing conflicts with other existing asynchronous and periodic processes.

First, a procedure is introduced that converts a single asynchronous process a_i into a corresponding new
15 periodic process "newpi". When determining newpi's deadline d_{newpi} , "room" (time) is left for all the hard deadline processes that have a shorter or equal deadline than that process's deadline, as follows:

$$20 \quad \sum_{p_j \in (S_P \cup S_p) \wedge d_{p_j} \leq d_{x_i}} \left\lceil \frac{d_{x_i}}{\text{prd}_{p_j}} \right\rceil * c_{p_j} + \sum_{a_j \in S_a \wedge d_{a_j} \leq d_{x_i} \wedge i \neq j} \left\lceil \frac{d_{x_i}}{\min_{a_j}} \right\rceil * c_{a_j}$$

In the above relationship, the deadline of the new periodic process d_{newpi} appears on both the left-hand
25 side and right-hand side thereof. The value of d_{newpi} as well as all other parameters of the new periodic process can be found with the following procedure for converting a single asynchronous process $a_i = (c_{ai}, d_{ai}, \min_{ai} \in S_a$ into a periodic Process $\text{newpi} = (o_{\text{newpi}}, r_{\text{newpi}}, c_{\text{newpi}},$
30 $d_{\text{newpi}}, \text{prd}_{\text{newpi}}) \in S_p$:

```

5      failure:= false;
       $r_{newp_i} := 0;$ 
       $c_{newp_i} := c_{a_i};$ 
       $d_{newp_i} := c_{a_i} + conversion\_room(a_i);$ 
      deadlinefound:= false;
      while not(deadlinefound) and not(failure) do
      begin
10          $d_{previous_i} := d_{newp_i};$ 
          $d_{newp_i} = c_{a_i} + conversion\_room(previous_i);$ 
         if  $d_{previous_i} = d_{newp_i}$  then deadlinefound:= true;
         if  $(d_{a_i} - d_{newp_i} + 1) \leq min_{a_i}$ 
         then
             $prd_{newp_i} := (d_{a_i} - d_{newp_i} + 1)$ 
         else
             $prd_{newp_i} := min_{a_i};$ 
15          $prd_{newp_i} := adjustperiod(prd_{newp_i});$ 
            {perform any necessary adjustments to  $prd_{newp_i}$ }
             $d_{new_i} := d_{a_i} - prd_{newp_i} + 1;$ 
            if  $(d_{newp_i} > d_{a_i})$  or  $(prd_{newp_i} < d_{newp_i})$ 
            then failure:= true
            else if deadlinefound
            then
20                 begin
                      $S_p := S_p \cup \{newp_i\};$ 
                      $S_a := S_a - \{a_i\};$ 
                 end;
            end;
      end
25
30

```

5 If it is assumed that the earliest time that asynchronous process a_i can make a request for execution is time t , then the range of the offset o_{newpi} is $(0, t + \text{prd}_{\text{newpi}} - 1)$.

Reference is made to Figures 10 and 13 for
10 examples of conversion of an asynchronous process into a periodic process.

In Figure 10, the periodic process $\text{newp}_A = (o_{\text{newp}_A}, r_{\text{newp}_A}, C_{\text{newp}_A}, d_{\text{newp}_A}, \text{prd}_{\text{newp}_A})$ translated from the asynchronous process $a_A = (c_{aA}, d_{aA}, \text{min}_{aA}) = (2, 7, 8)$, where $r_{\text{newp}_A} =$
15 $0, C_{\text{newp}_A} = c_{aA} = 2, d_{\text{newp}_A} = c_{aA} = 2, \text{prd}_{\text{newp}_A} = \min(d_{aA} - d_{\text{newp}_A} + 1, \text{min}_{aA}) = \min(7 - 2 + 1, 8) = 6, 0 \leq o_{\text{newp}_A} = 0, \leq \text{prd}_{\text{newp}_A} - 1 = 5$. If the offset of periodic process newp_A is set to 0, i.e. o_{newp_A} , then the periodic process executions $\text{newp}_{A0}, \text{newp}_{A1}, \text{newp}_{A2}, \text{newp}_{A3}, \text{newp}_{A4}, \text{newp}_{A5} \dots$
20 start at the times 0, 6, 12, 18, 24, 30, ... respectively, and if the asynchronous request times R_{a0}, R_{aA1}, R_{aA2} are 1, 9, 17, 27, then the asynchronous process executions $a_{A0}, a_{A1}, a_{A2}, a_{A3}$ start at the times 6, 12, 18, 30 respectively. a_{A0} executes in the time slot of newp_{A1} ,
25 a_{A1} executes in the time slot of newp_{A2} , a_{A2} executes in the time slot of newp_{A3} , and a_{A3} executes in the time slot of newp_{A5} .

In Figure 13, the periodic process $\text{newp}_A = (o_{\text{newp}_A}, r_{\text{newp}_A}, C_{\text{newp}_A}, d_{\text{newp}_A}, \text{prd}_{\text{newp}_A})$ translated from the asynchronous
30 process $a_A = (c_{aA}, d_{aA}, \text{min}_{aA}) = (2, 7, 8)$, where $r_{\text{newp}_A} = 0, C_{\text{newp}_A} = c_{aA} = 2, d_{\text{newp}_A} = c_{aA} = 2, \text{prd}_{\text{newp}_A} = \min(d_{aA} -$

$d_{\text{newpA}} + 1, \min_{aA}) = \min(7-2+1, 8) = 6, 0 \leq 0_{\text{newpA}} = 0, \leq$
 $\text{prd}_{\text{newpA}} - 1 = 5$. If the offset of periodic process newpA
 is set to 5, the periodic process executions newpA_0 ,
 newpA_1 , newpA_2 , newpA_3 , newpA_4 , $\text{newpA}_5 \dots$ start at the times
 5, 11, 17, 23, 29, 35, ..., and if the asynchronous always
 makes requests at the earliest possible time and at the
 highest possible rate, the first five asynchronous
 request times R_{a0} , R_{aA1} , R_{aA2} , R_{aA3} , R_{aA4} are 0, 8, 16, 24,
 32, then the asynchronous process executions a_{A0} , a_{A1} ,
 10 a_{A2} , a_{A3} start at the times 5, 11, 17, 29, 35
 respectively. A_{A0} executes in the time slot of newpA_1 ,
 a_{A1} executes in the time slot of newpA_2 , a_{A2} executes in
 the time slot of newpA_2 , and a_{A3} executes in the time
 slot of newpA_3 , a_{A4} executes in the time slot of newpA_4 ,
 15 and a_{A5} executes in the time slot of newpA_5 , etc.

In some cases, when the lengths of periods are
 relatively prime, the length of the LCM of the periods
 could become inconveniently long. A function
 "adjustperiod" can be used to adjust $\text{prd}_{\text{newpi}}$, whenever
 20 the LCM became inconveniently long.

(See Example A below and Figures 15 and 16 for
 an example of the use of the adjustperiod Procedure).
 The adjust period function will be described below in
 the section related to construction of a feasible pre-
 25 run-time schedule for the P-h_k processes.

Example 2

Assuming that in addition to the processes in
 30 Example 1 above, the following A-h-k process:
 $A = : c_{a3} = 10, d_{a3} = 114, \min_{a3} = 114$.

If the procedure above is used to convert a_3 into
a
periodic process $newp_3$, prior to entering the while
loop,

$$5 \quad d_{newp3} = c_{a3} + c_{p5} + c_{a0} + c_{a1} = 10 + 16 + 2 + 2 = 30.$$

In the first iteration of the
while loop, $d_{\{previous\}} = d_{\{newp_3\}} = 30$;
 $d_{\{newp_3\}} = c_{\{a_3\}} + c_{\{a_0\}} + c_{\{a_1\}}$
 $= 10 + 2 + 2 = 14.$

$$10 \quad \text{Since } d_{previous} \neq newp3, \text{ deadlinefound} = \text{false}.$$

In the second iteration of the while loop,
 $d_{previous} = d_{newp3} = 14$; $d_{newp3} = c_{a3} + c_{a0} + c_{a1} = 10 + 2 + 2 =$
14.

$$15 \quad \text{Since } d_{previous} = d_{newp3}, \text{ deadlinefound} = \text{true},$$

$$prd_{newp3} = (d_{a3} - d_{newp3} + 1) = 114 - 14 + 1 = 100.$$

If we use the adjustperiod function and
select_exp_upperbounds procedure described herein with
reference to constructing a feasible pre-run-time
schedule for the P-h-k processes to adjust the period
20 prd_{newp3} , by using $prd_{max} = prd_{p4} = 200$, and the following
initial exponent upperbound values: $exp2_{init} = 5$, $exp3_{init}$
 $= 3$, $exp5_{init} = 2$, $exp7_{init} = 0$, and use the value 24 for
the parameters C_m , C_{m11} , C_{m7} , C_{m5} , C_{m3} , C_{m2} and C_d , C_{d7} , C_{d5} , C_{d3} ,
 C_{d2} and the value 0 for C_{e7} , C_{e5} , C_{e3} , C_{e2} and the value 0
25 for C_{e7} , C_{e5} , C_{e3} , C_{e2} , and the values 0, 1, 2 for C_{e57} ,
 C_{e35} , C_{e23} , respectively, then the select_exp_upperbounds
procedure will produce the following values for the
exponent upperbounds:

$$30 \quad \begin{aligned} &exp2 = 5, \quad exp3 = 3, \quad exp5 = 2, \quad exp7 = 0, \quad exp11 = \\ &0. \end{aligned}$$

$$RPC_{a_j} = \left(\sum_{p_i \in (S_P \cup S_P) \wedge L_{a_j} \leq L_{p_i}} \frac{\lceil \frac{d_{p_i} - r_{p_i}}{\min_{a_j}} \rceil c_{a_j}}{prd_{p_i}} \right) + \frac{c_{a_j}}{\min_{a_j}}$$

5

In general if an asynchronous process has a long minimum time between consecutive requests, then that asynchronous process is more likely to require less processor capacity to be reserved if it is treated as an
 10 A-h-k-a process compared with treating it as an A-h-k-p process.

A procedure for converting a set of asynchronous processes

$\{(c_{ai}, d_{ai}, \min_{ai}) \mid i = 0, 1, \dots, n\} \subset S_A$ into a set of
 15 periodic processes $S_p = \{(o_{pi}, r_{pi}, c_{pi}, d_{pi}, prd_{pi}) \mid i = 0, 1, \dots, n\}$ follows:

S_p : = original set of P-h-k processes;

S_A : = original set of A-h-k processes;

S_a : = S_A ;

20 S_p : = emptyset;

numofchanges:=0;

changes:= true;

while (changes) and (numofchanges < someupperlimit) do
 begin

25 changes:= false;

begin

for each $a_j \in S_A$, in the order of increasing
 deadlines do

30 begin

The procedure described earlier should be used to tentatively convert each A-h-k asynchronous process $a_j \in S_A$ into a new periodic process $newp_j \in S_p$ with the same index. Note that this conversion depends not only
5 on a_j , but also on the entire set of new periodic processes in S_p , the original set of P-h-k processes in S_p , and the set of A-h-k-a processes in S_a

```

newp_j := Tentatively_convert_into_new_periodic_process(a_j, S_p, S_P, S_a)
if (d_newp_j ≤ d_a_j) and (prd_newp_j ≥ d_newp_j)
then
begin
  c_newp_j' = c_newp_j + adjusted_capacity(newp_j);
  RPC_newp_j := c_newp_j' / prd_newp_j;
  RPC_a_j := (∑_{p_i ∈ (S_P ∪ S_p) ∧ L_a_j ≤ L_p_i} \frac{\lceil \frac{d_{p_i} - r_{p_i}}{min_{a_j}} \rceil c_{a_j}}{prd_{p_i}}) + \frac{c_{a_j}}{min_{a_j}};
  if threshold(a_j) * RPC_newp_j ≤ RPC_a_j
  then
  begin
    if {newp_j} ∉ S_p
    {or if the version of newp_j in S_p is different
    from the newly converted version of newp_j}
    then
    begin
      changes := true;
      S_p := S_p ∪ {newp_j};
      {add new periodic process newp_j
      converted from a_j to the periodic set S_p,
      replacing any older version of newp_j in S_p}
    end;
    if {a_j} ∈ S_a then
      S_a := S_a - {a_j};
      {remove a_j from asynchronous set S_a}
    end
  else {threshold(a_j) * RPC_newp_j > RPC_a_j}
  begin
    if {a_j} ∉ S_a then
    begin

```

```

        changes:= true;
         $S_a := S_a \cup \{a_j\}$ ;
        {add  $a_j$  to asynchronous set  $S_a$ }
    end;
    if  $\{newp_j\} \in S_p$  then
         $S_p := S_p - \{newp_j\}$ ;
        {remove  $p_j$  from periodic set  $S_p$ }
    end;
end;
end;
for each  $a_j \in S_A$ , in the order of decreasing deadlines do
begin
    (repeat the same procedure that was done in the order of
    increasing deadlines for each  $a_j \in S_A$  above)
end;
if changes then
    numofchanges:= numofchanges + 1;
end;
end;

```

15

At the end of the procedure, the final set of A-h-k-a processes is S_a and the final set of new periodic processes converted from A-h-k-p processes is S_p .

Above, the range of the offset for each new
 20 periodic process $newp_i$, o_{newp_i} is $(0, newp_i]$. The user can decrease or increase each "threshold(a_j)" value in the procedure above, to increase or decrease the likelihood that each A-h-k process a_j will be converted into a P-h-k process, depending on the application requirements.

25 Setting the threshold value of a certain asynchronous process to a high value so that it is unlikely to be converted into a new periodic process, may in some cases increase the schedulability of that process; in other cases converting an asynchronous process into a periodic
 30 process may increase schedulability (see example 14); but increasing schedulability may not be the only

objective in a particular application. In some cases,
 one may prefer that a certain A-h-, process should be
 converted into a new periodic process whenever possible,
 to reduce scheduling overhead and/or simplify the timing
 5 analysis and make it easier to predict the system's
 behavior.

Example 3

Assuming that the threshold value for each A-h-k
 10 process is set as follows: threshold (a_0) = 10,
 threshold (a_1) = 10, threshold (a_2) = 1, threshold (a_3) =
 2.5, threshold (a_9) = 1, the procedure above will
 determine the following for each of the processes in
 Examples 1 and 2:

15

a_0 :

$$d_{newp_0} = 2; prd_{newp_0} \leq \min(d_{a_0} - d_{newp_0} + 1, \min_{a_0}) = 2 - 2 + 1 = 1 < c_{newp_0} = 2$$

a_0 will NOT be converted into a new periodic process and will remain asynchronous
 and belong to the set A-h-k-a.

a_1 :

$$d_{newp_1} = c_{a_1} + \lceil d_{newp_1} / \min_{a_0} \rceil c_{a_0} = 2 + \lceil 4/1000 \rceil 2 = 4$$

$$prd_{newp_1} = \min(d_{a_1} - d_{newp_1} + 1, \min_{a_1}) = 7 - 4 + 1 = 4$$

$$RPC_{newp_1} = c_{newp_1} / prd_{newp_1} = 4/4 = 1$$

$$RPC_{a_1} = \lceil (d_{newp_3} - r_{newp_3}) / \min_{a_1} \rceil c_{a_1} / prd_{newp_3} + \lceil (d_{p_4} - r_{p_4}) / \min_{a_1} \rceil c_{a_1} / prd_{p_4}$$

$$+ \lceil (d_{p_5} - r_{p_5}) / \min_{a_1} \rceil c_{a_1} / prd_{p_5} + \lceil (d_{p_6} - r_{p_6}) / \min_{a_1} \rceil c_{a_1} / prd_{p_6} + \lceil (d_{p_7} - r_{p_7}) / \min_{a_1} \rceil$$

$$c_{a_1} / prd_{p_7}$$

$$+ c_{a_1} / \min_{a_1} = 2/100 + 2/200 + 2/200 + 2/200 + 2/200 + 2/1000$$

$$= 0.062 < \text{threshold}(a_1) * RPC_{newp_1} = 10 * 1 = 10$$

a_1 will NOT be converted into a periodic process, and will remain asynchronous and
 belong to the set A-h-k-a.

a_3 :

$$d_{newp_3} = c_{a_3} + \lceil d_{newp_3} / \min_{a_0} \rceil c_{a_0} + \lceil d_{newp_3} / \min_{a_1} \rceil c_{a_1} = 10 + \lceil 30/1000 \rceil 2 + \lceil 30/1000 \rceil 2$$

$$= 14$$

$$prd_{newp_3} = \min(d_{a_3} - d_{newp_3} + 1, \min_{a_3}) = 114 - 14 + 1 = 101$$

After the adjustperiod function is applied (see Example 2):

$$prd_{newp_3} = adjustperiod(101) = 100;$$

$$d_{newp_3} = d_{a_3} - prd_{newp_3} + 1 = 114 - 100 + 1 = 15;$$

$$RPC_{newp_3} = c_{newp_3}' / prd_{newp_3} = 14/100 = 0.14;$$

$$RPC_{a_3} = [(d_{p_4} - r_{p_4}) / min_{a_3}] c_{a_3} / prd_{p_4} + [(d_{p_6} - r_{p_6}) / min_{a_3}] c_{a_3} / prd_{p_6} \\ + [(d_{p_7} - r_{p_7}) / min_{a_3}] c_{a_3} / prd_{p_7} + c_{a_3} / min_{a_3} = 20/200 + 20/200 + 20/200 + 10/113 = \\ 0.388 \geq threshold(a_3) * RPC_{newp_3} = 2.5 * 0.14 = 0.35$$

a_3 will be converted into a new periodic process $newp_3 = (r_{newp_3}, c_{newp_3}, d_{newp_3}, prd_{newp_3}) = (0, 10, 14, 100)$.

a_2 :

$$d_{newp_2} = c_{a_2} + [d_{newp_2} / min_{a_0}] c_{a_0} + [d_{newp_2} / min_{a_1}] c_{a_1} + [d_{newp_2} / prd_{newp_3}] c_{newp_3} \\ + [d_{newp_2} / prd_{p_5}] c_{p_5} = 10 + [40/1000]2 + [40/1000]2 + [40/100]10 + [40/200]16 = \\ 40$$

$$prd_{newp_2} = min(d_{a_2} - d_{newp_2} + 1, min_{a_2}) = 239 - 40 + 1 = 200$$

$$RPC_{newp_2} = c_{newp_2}' / prd_{newp_2} = 14/200 = 0.07$$

$$RPC_{a_2} = c_{a_2} / min_{a_2} = 10/1000 = 0.01 < threshold(a_2) * RPC_{newp_2} = 1 * 0.07 = 0.07$$

a_2 will NOT be converted into a periodic process, and will remain asynchronous and belong to the set A-h-k-a.

a_9 :

$$d_{newp_9} = c_{a_9} + [d_{newp_9} / min_{a_0}] c_{a_0} + [d_{newp_9} / min_{a_1}] c_{a_1} + [d_{newp_9} / min_{a_2}] c_{a_2} \\ + [d_{newp_9} / prd_{newp_3}] c_{newp_3} + [d_{newp_9} / prd_{p_5}] c_{p_5} = 10 + [50/1000]2 + [50/1000]2 \\ + [50/1000]10 + [50/100]10 + [50/200]16 = 50$$

$$prd_{newp_9} = min(d_{a_9} - d_{newp_9} + 1, min_{a_9}) = 259 - 50 + 1 = 200$$

$$RPC_{newp_9} = c_{newp_9}' / prd_{newp_9} = 24/200 = 0.12$$

$$RPC_{a_9} = c_{a_9} / min_{a_9} = 10/1000 = 0.01 < threshold(a_9) * RPC_{newp_2} = 1 * 0.12 = 0.$$

a_9 will NOT be converted into a periodic process, and will remain asynchronous and belong to the set A-h-k-a.

Except for prd_{newp3} that was adjusted from 101 to 100, all other periods in this example remain unchanged by the $adjustperiod$ function.

An alternative case where $threshold(a_3)$ is set to an arbitrary large value, ensuring that A-h-k process a_3 is not converted into a periodic process, is discussed below with respect to Example 13.

There exists a circular dependency relationship between the calculation of the RPC for each A-h-k-a process and the determination of the set of A-h-k-a processes. The calculation of the RPC for each A-h-k-a process depends on the original set of P-h-k processes S_p , the set of new periodic processes S_p converted from A-h-k-p periodic processes, and the set of processes that remain asynchronous S_a .

However determining which A-h-k process should be converted into a new periodic process in turn depends on the calculation of the RPC amount for the corresponding A-h-k-a process. It is for this reason that an iterative procedure is preferred to be used for this task.

Below, all periodic processes with hard-deadlines and known characteristics (including all new periodic processes in S_p that are converted from A-h-k-p processes, and the original set of P-h-k processes in S_p) will be referred to as P-h-k processes.

Step 2:

A feasible pre-run-time schedule for the P-h-k processes is constructed. In this step, the

schedulability of the set of all periodic processes with hard deadlines and known characteristics (P-h-k processes) are determined using their adjusted computation times, and a feasible pre-run-time schedule
 5 that satisfies all the specified constraints is constructed.

In some cases, when the lengths of periods are relatively prime, the length of the LCM of the periods could become inconveniently long. One may use a
 10 function "adjustperiod" to adjust the period length of each periodic process, whenever the LCM becomes inconveniently long.

Preferred function and procedures for adjusting the periods of periodic processes in order to reduce the
 15 Least Common Multiple (LCM) of the period lengths, and the pre-run-time schedule length are as follows:

```
function adjustperiod(prd);
begin
  j:= 1;
  while refprd[j] ≤ prd do
    j:= j + 1;
  adjustperiod:= refprd[j-1];
end;
```

```
procedure generate_refprds(exp2, exp3, exp5, exp7, exp11);
begin
  count:= 1;
  for i:= 0 to exp2 do
    begin
      for j:= 0 to exp3 do
        begin
          for k:= 0 to exp5 do
            begin
              for l:= 0 to exp7 do
                begin
```

```

        for f:= 0 to exp11 do
            begin
                refprd[count]:=  $2^i * 3^j * 5^k * 7^l * 11^f$ ;
                count:= count + 1;
            end;
        end;
    end;
end;
for i:= 1 to count - 2 do
    begin
        for j:= i + 1 to count - 1 do
            begin
                if refprd[i] > refprd[j]
                then
                    begin
                        temp:= refprd[i];
                        refprd[i]:= refprd[j];
                        refprd[j]:= temp;
                    end;
                end;
            end;
        end;
    end;
end;

procedure select_exp_upperbounds( $prd_{max}$ ,  $exp2_{init}$ ,  $exp3_{init}$ ,  $exp3_{init}$ ,  $exp5_{init}$ ,
 $exp7_{init}$ ,  $exp11_{init}$ ,  $C_m$ ,  $C_{m11}$ ,  $C_{m7}$ ,  $C_{m5}$ ,
 $C_{m3}$ ,  $C_{m2}$ ,  $C_d$ ,  $C_{d7}$ ,  $C_{d5}$ ,  $C_{d3}$ ,  $C_{d2}$ ,
 $C_{e7}$ ,  $C_{e5}$ ,  $C_{e3}$ ,  $C_{e2}$ ,  $C_{e57}$ ,  $C_{e35}$ ,  $C_{e23}$ );

begin
    exp2:=  $exp2_{init}$ ;
    exp3:=  $exp3_{init}$ ;
    exp5:=  $exp5_{init}$ ;
    exp7:=  $exp7_{init}$ ;
    exp11:=  $exp11_{init}$ ;
    n:=  $2^{exp2} * 3^{exp3} * 5^{exp5} * 7^{exp7} * 11^{exp11}$ ;
    stop:= false;
    if ( $C_m * prd_{max} > n$ ) then
        begin
            while(( $C_m * prd_{max} > n$ ) and (not(stop))) do
                begin

```

```

if ( $C_{m11} * prd_{max} \geq 11 * n$ )
then
begin
   $n := n * 11;$ 
   $exp11 := exp11 + 1;$ 
end
else if ( $(C_{m7} * prd_{max}) \geq (7 * n)$ )
then
begin
   $n := n * 7;$ 
   $exp7 := exp7 + 1;$ 
end
else if ( $(C_{m5} * prd_{max}) \geq (5 * n)$ )
then
begin
   $n := n * 5;$ 
   $exp5 := exp5 + 1;$ 
end
else if ( $(C_{m3} * prd_{max}) \geq (3 * n)$ )
then
begin
   $n := n * 3;$ 
   $exp3 := exp3 + 1;$ 
end
else if ( $(C_{m2} * prd_{max}) \geq (2 * n)$ )
then
begin
   $n := n * 2;$ 
   $exp2 := exp2 + 1;$ 
end
else
begin
  stop:= true;
end;

```



```

end;
end
else
begin { $C_m * prd_{max} \leq n$ }
  while((( $C_d * prd_{max}$ ) <  $n$ ) and (not(stop))) do
  begin
    if ((( $C_{d7} * prd_{max}$ )  $\leq$  ( $n \div 7$ )) and ( $exp7 > C_{e7}$ ) and (( $exp5 - exp7$ )  $\leq C_{e57}$ ))
    then
    begin
       $n := n \div 7$ ;
       $exp7 := exp7 - 1$ ;
    end
  else if ((( $C_{d5} * prd_{max} \leq (n \div 5)$ ) and ( $exp5 > C_{e5}$ ) and (( $exp3 - exp5$ )  $\leq C_{e35}$ ))
  then
  begin
     $n := n \div 5$ ;
     $exp5 := exp5 - 1$ ;
  end
  else if ((( $C_{d3} * prd_{max} \leq (n \div 3)$ ) and ( $exp3 > C_{e3}$ ) and (( $exp2 - exp3$ )  $\leq C_{e23}$ ))
  then
  begin
     $n := n \div 3$ ;
     $exp3 := exp3 - 1$ ;
  end
  else if ((( $C_{d2} * prd_{max} \leq (n \div 2)$ ) and ( $exp2 > C_{e2}$ ))
  then
  begin
     $n := n \div 2$ ;
     $exp2 := exp2 - 1$ ;
  end
  else
  begin
    stop := true;
  end;
end;
end;
end;

```

The function `adjustperiod` uses a sorted list of reference periods "refprd" to adjust the length of the period of each periodic process. It adjusts the length
 5 of the period of each periodic process "prd" to the largest reference period `refprd(x)` that is smaller or equal to `prd`.

The procedure `generateprd` creates a sorted list of reference periods "refprd", in which each reference
 10 period `refprd(x)` is equal to $2^i * 3^j * 5^k * 7^l * 11^f$, ..., for some integers i, j, k, l, f, \dots .

where

$0 \leq i \leq \text{exp2}, 0 \leq j \leq \text{exp3}, 0 \leq k \leq \text{exp5}, 0 \leq l \leq \text{exp7}, 0 \leq f \leq \text{exp11}, \dots$

15 `exp2, exp3, exp5, exp7, exp11, ...`, are the upperbounds on the exponents i, j, k, l, f, \dots , that are applied to the prime numbers 2, 3, 5, 7, 11, ...

In order to avoid redundancy, we will illustrate and discuss the methods using only the first five prime
 20 numbers 2, 3, 5, 7, 11. It is possible to use more prime numbers, that is, 13, 17, 19, etc., if larger period lengths are needed. The methods shown here can be extended to include any additional prime numbers should the need arise.

25 The procedure `select_exp_upperbounds` selects the exponent upperbound values `exp2, exp3, exp5, exp7, exp11`, based on the maximum length of the original periods `prdmax`, and a set of initial values `exp2init, exp3init, exp5init, exp7init, exp11init`, for `exp2, exp3,`
 30 `exp5, exp7, exp11`, respectively. The Least Common

Multiple (LCM) of the periods will be bounded by $2^{\text{exp2}} * 3^{\text{exp3}} * 5^{\text{exp5}} * 7^{\text{exp7}} * 11^{\text{expl1}}$.

There is a tradeoff in adjusting periods: shorter adjusted periods result in shorter LCMs of the periods, and consequently, shorter pre-run-time schedule lengths and fewer instances of new processes; but will increase the processor utilization and waste more processor capacity. This tradeoff can be fine tuned using the exponent upperbound values exp2, exp3, exp5, exp7, expl1.

In general, larger values of the exponent upperbounds will increase the chances of the adjusted period length being close to the original schedule length, and reduce wasted processor capacity but will increase the LCM of the periods and schedule length. When the exponent upperbound associated with a larger prime number, say expl1, is increased relative to the exponent upperbounds associated with smaller prime numbers, say exp7, exp5, exp3, exp2, while the exponent upperbounds associated with the smaller prime numbers are not smaller than some minimum value, e.g., $\min\{\text{exp7}\} = 1$, $\min\{\text{exp5}\} = 2$, $\min\{\text{exp3}\} = 3$, $\min\{\text{exp2}\} = 5$, respectively, it will also have the effect of reducing wasted processor capacity but increasing the LCM and schedule length.

The procedure select_exp_upperbounds, allows exp2, exp3, exp5, exp7, expl1, to be fine tuned according to specific application requirements. In this procedure, larger values of the parameters C_m , C_{m11} , C_{m7} , C_{m5} , C_{m3} , C_{m2} , C_d , C_{d7} , C_{d5} , C_{d3} , C_{d2} ; and smaller values for the parameters C_{e7} , C_{e5} , C_{e3} , C_{e2} , C_{e57} , C_{e35} , C_{e23} , are more

pr_d{Keyboard/Mouse} = 92400 (original 100000).

The LCM of the periods will be 277200, which is 3 times the length of the maximum adjusted process period length.

5 Assume now that such a high precision is not required when adjusting the periods of the processes with maximum process length, then a smaller value, say 1, may be used for the parameters C_m , C_{m11} , C_{m7} , C_{m5} , C_{m3} , C_{m2} , and C_d , C_{d7} , C_{d5} , C_{d3} , C_{d2} , and still use the value 0
10 for C_{e7} , C_{e5} , C_{e3} , C_{e2} and the values 0, 1, 2, for C_{e57} , C_{e35} , C_{e23} , respectively.

Assume that the same initial exponent upperbound values are used:

exp_{2init} = 5, exp_{3init} = 3, exp_{5init} = 2,

15 exp_{7init} = 1, exp_{11init} = 0. The select_exp_upperbounds procedure will produce the following values for the exponent upperbounds:

exp₂ = 5, exp₃ = 3, exp₅ = 2, exp₇ = 1, exp₁₁ = 0.

After the generate_refprd procedure has used the
20 above exponent upperbounds to compute the sorted list of reference periods in refprd, the adjustperiod function will use the sorted list of reference periods to compute the following adjusted periods:

Pr_d{CD-Audio} = 360 (original 364),

25 pr_d{ISDN} = 630 original 667,

pr_d{Voice} = 720 (original 727),

pr_d{Keyboard/Mouse} = 75600 (original 100000).

The LCM of the periods will be 75600, which is 1 times the length of the maximum adjusted process period
30 length.

for $o_{p_n} := \text{offsetlowerbound}(p_n)$ to $\text{offsetupperbound}(p_n)$ do
begin {loop body}

Construct a schedule for all occurrences of all the processes in S_p
within the interval $[0, \max\{o_{p_i} | \forall p_i\} + 3 * \text{prd}_{LCM}]$;

If the following conditions are satisfied, then set $\text{success} := \text{true}$; and
exit from the procedure:

There must exist a point t in the schedule, such that:

(1) The subschedule in the interval $[t, t + \text{prd}_{LCM}]$ is equal to the
subschedule in the interval $[t + \text{prd}_{LCM}, t + 2 * \text{prd}_{LCM}]$;

(2) All the occurrences of all processes in S_p within the interval
 $[t, t + \text{prd}_{LCM}]$ must be included in the subschedule in $[t, t + \text{prd}_{LCM}]$;

(3) All the occurrences of all processes in S_p within the interval
 $[0, t + \text{prd}_{LCM}]$ must satisfy all their respective timing constraints.

end; {loop body}

end; {for loops}

if success is true then set the "*initial part of the pre-run-time schedule*" $S_0(t)$ to be
the subschedule in the interval $[0, t]$, and set the "*repeating part of the pre-run-time
schedule*" $S_{LCM}(\text{prd}_{LCM})$ to be the subschedule in the interval $[t, t + \text{prd}_{LCM}]$;

end. {procedure}

The optimal scheduling method in the aforementioned
1990 article by Xu and Parnas that constructs a feasible
20 schedule for a set of processes with release times,
deadlines, precedence and exclusion relations, can be
used for this purpose. If the processes are to be
scheduled on more than one processor, the optimal
scheduling method as described in the aforementioned 1993
25 article by Xu and Parnas that constructs a non-
preemptive feasible schedule for a set of processes
with release times, deadlines, precedence and exclusion
relations on multiple processors, can be used for this
purpose. Note that it is not strictly necessary to use
30 the scheduling method of the 1990 or the 1993 article.
One may use any method for this step, the only

requirements being that the method should be capable of constructing a feasible schedule for a set of periodic processes, in which all the specified constraints and dependencies between the processes are satisfied.

5

Example 4

Assume that the following precedence relations and

10 exclusion relations must be satisfied for the processes in

Examples 1-3 above:

p_6 precedes p_7 ;

a_2 excludes a_3 , a_9 ;

15 a_3 excludes a_2 , p_4 , p_6 ;

a_9 excludes a_2 ;

p_4 excludes a_3 , p_5 , p_6 ;

p_5 , p_6 excludes p_4 ;

p_5 excludes p_6 ;

20 p_6 excludes a_3 , p_5 .

If the method in the aforementioned 1990 Xu and Parnas article is used to schedule all the P-h-k processes $newp_3$, p_4 , p_5 , p_6 , p_7 using their adjusted computation times, the feasible schedule will be found
25 in Figure 1. This guarantees that all the P-h-k processes are schedulable.

In Example 4 above, a feasible schedule for the case in which the offsets of all the periodic processes are zero was shown. Below is another example to show
30 how the procedure given above can use existing methods to schedule a set of periodic processes together with a

set of new periodic processes that are converted from asynchronous processes, where the original periodic processes and the new periodic processes may have non-zero offsets.

5

Example B

Assume the following A-h-k process a_A (see Fig.

10):

10 $a_A: c_{aA} = 2; d_{aA} = 7; \min_{aA} = 8.$

Assume also the following two periodic processes

p_B and p_C (see Fig. 11 and Fig. 12):

$p_B: o_{pB} = 0; r_{pB} = 1; c_{pB} = 3; d_{pB} = 4$

$\text{prd}_{pB} = 12.$

15 $p_C: o_{pC} = 7; r_{pC} = 0; c_{pC} = 4; d_{pC} = 4$

$\text{prd}_{pC} = 12.$

Assume that the application requires p_B, p_C to have fixed offset values of 0 and 7 respectively.

Assuming that asynchronous process a_A may make
20 its first request at time 0, the procedure for converting a set of asynchronous processes into a set of periodic processes given earlier, could convert a_A into the following new periodic process:

$\text{newp}_A: r_{\text{newp}_A} = 0; c_{\text{newp}_A} = 2;$

25 $d_{\text{newp}_A} = 2; \text{prd}_{\text{newp}_A} = 6; \text{ and } 0 \leq o_{\text{newp}_A} \leq \text{prd}_{\text{newp}_A} - 1 = 5.$

The lowerbound of the offset of newp_A is 0, and the upperbound of the offset of newp_A is 5 (see Figure 10 and Figure 13).

The procedure for constructing a feasible pre-
30 run-time schedule for a given set of periodic processes with offsets given above will try each offset value of

O_{newpA} within the range of $0, prd_{newpA} - 1 = (0, 5)$, when trying to find a feasible schedule for $newp_A$, p_B , and p_C . When the last value in that range, $O_{newpA} = 5$ is used, the method in the 1990 article by Xu and Parnas would
 5 find the feasible schedule illustrated in Figure 14. A feasible schedule is found for $newp_A$, p_B and p_C , when $O_{newpA} = 5$ and $O_{pD} = 2$. It is assumed that the application requires that $O_{pC} = 7$, $O_{pB} = 0$ and since asynchronous process a_A may make its first request at
 10 time $0, 0 \leq O_{newpA} \leq prd_{newpA} - 1 = 5$. The feasible schedule consists of a non-repeating initial schedule S_{01} for the interval $(0, 1)$, and a repeating schedule S_{LCM12} that is of length equal to the Least Common Multiple of the periods of $newp_A$, p_B , p_C , and p_D , which
 15 is $LCM(6, 12, 12, 12) = 12$.

Assume that in addition to the periodic processes $newp_A$, p_B , p_C , the following periodic process p_D exists (as shown in Figure 15):
 $p_D: r_{pD} = 2, c_{pD} = 1, d_{pD} = 4,$
 20 $prd_{pD} = 13, 0 \leq O_{pD} \leq 4$.

If the "adjustperiod" function is applied to the periods of $newp_A$, p_B , p_C , and p_D , then p_D 's period prd_{pD} will be shortened from length 13 to length 12, resulting in the modified periodic process $p_D = O_{pD}, r_{pD}, c_{pD}, d_{pD},$
 25 prd_{pD} where $r_{pD} = 2, c_{pD} = 1, d_{pD} = 4, prd_{pD} = 12, 0 \leq O_{pD} \leq 4$, as shown in Figure 16.

The other periods prd_{newpA} , prd_{pB} , and prd_{pC} remain unchanged after the adjustperiod procedure is applied. Assuming that the application allows the offset of p_D to
 30 be in the range of $(0, 4)$, the procedure for constructing a feasible pre-run-time schedule for a

As shown in Figure 17, the periodic process $p_D = o_{pD}, r_{pD}, c_{pD}, d_{pD}, prd_{pD}$ where $r_{pD} = 2, c_{pD} = 1, d_{pD} = 4, prd_{pD} = 12, 0 \leq o_{pD} \leq 4$, where the offset of p_D is set to a fixed value $o_{pD} = 2$ during run-time scheduling when it is attempted to construct a feasible pre-run-time schedule for $newp_A, p_B, p_C$ and p_D .

As shown in Figure 18, a feasible schedule is shown for newp_A , p_B , p_C and p_D , when $o_{\text{newp}_A} = 5$ and $o_{p_D} = 2$. It is assumed that the application requires that $o_{p_C} = 7$, $o_{p_B} = 0$, and $0 \leq o_{p_D} \leq 4$, and asynchronous process a_A may make its first request at time 0. The feasible schedule consists of a non-repeating initial schedule $S_0(1)$ for the interval $(0,1)$, and a repeating schedule $S_{\text{LCM}}(12)$ that is of length equal to the least common multiple of the periods of newp_A , p_B , p_C and p_D , which is $\text{LCM}(6, 12, 12, 12) = 12$.

The feasible schedule consists of a non-repeating initial schedule $S_{0(1)}$ for the interval $[0,1]$, and a repeating schedule $S_{LCM(12)}$ that is of length equal to the Least Common Multiple of the periods of $newp_A$, p_B , p_C , and p_D , which is $LCM(6, 12, 12, 12) = 12$.

The following notation is used below to denote the beginning and end of the time slot of each process in a pre-run-time schedule, the actual start time and actual completion time of each process, and the most recent actual arrival time of an asynchronous process at run-time. This notation will be used extensively below.

$s(p)$ is the time of the beginning of the time slot that was reserved for periodic process p in the pre-run-time schedule.

$S'(x)$ is the actual time that periodic process or asynchronous process x was/will be put into execution at run-time. At any time t , if periodic or asynchronous process x has been put into execution after or at time t , then $t \leq s'(x)$ is true, otherwise $\neg t \leq s'(x)$ is true.

$s'(p)$ depends on the arrival times of asynchronous processes a_j and whether and at what time they preempt periodic processes. $s'(p)$ also depends on the actual execution times of other processes that are executed prior to p 's execution at run-time.

$e(p)$ is the time of the end of the time slot that was reserved for periodic process p in the pre-run-time schedule.

$e'(x)$: the actual time at which asynchronous or periodic process x 's execution ends at run-time. At any time t , if periodic or asynchronous process x 's execution has ended after or at time t , then $t \leq e'(x)$ is true; otherwise if x 's execution has not ended before or at time t , then $\neg t \leq e'(x)$ is true.

$R'(a)$: the most recent actual arrival time of asynchronous process a at run-time. At any time t , if

asynchronous process a has arrived before or at time t , then $R'(a) \leq t$ is true, otherwise $\neg R'(a) \leq t$ is true. At any time t , if asynchronous process a has arrived at least once before time t and after or at time 0, then 0
5 $\leq R'(a)$ is true, otherwise if a has never arrived before or at time t , then $\neg 0 \leq R'(a)$ is true.

Example 5

10 In Figure 1, the time slot that is assigned to the
the
P-h-k process p_6 in the feasible pre-run-time schedule begins at time 114, and ends at time 144, so $s(p_6) = 114$, $e(p_6) = 144$. The length of the time slot assigned
15 to p_6 in the pre-run-time schedule is equal to the adjusted computation time of p_6 , i.e., c_{p_6}' , which includes the time reserved in case p_6 is preempted by A-h-k-a processes with less latitude in an actual execution.

20 Fig. 2 shows a possible actual execution of the P-h-k processes when they are scheduled at run-time together with the A-h-k-a processes a_0, a_1, a_2, a_9 , together with the P-h-k processes of Figure 1. In this execution, the worst case response time of a_2 of the A-h-k process $Re_{a_2} = \max\{RE(a_2, t_s)\} = RE(a_2, 82) = e'(a_2) - R_{a_2} = 166 - 82 = 84$. (the details are explained in
25 Example 7 below, see particularly step 3).

Note that in Figure 2 the relative order in which P-h-k processes are executed at run-time, is kept
30 the same as the relative order of the time slots that are assigned to those periodic processes in the feasible

pre-run-time schedule in Fig. 1. Note also that the length of the computation time indicated for each P-h-k process is its original computation time, not its adjusted computation time. For example, in Fig. 2,

5 $s'(p_6) = 114$, $e'(p_6) = 140$.

Step 3: Determine the worst case response times of the A-h-k-a processes

- 10 A-h-k-a processes are scheduled at run-time by the A-h-k-a Scheduler Process (see the description later which describes scheduling A-h-k-a processes), but their worst-case response times are determined before run-time in this step. Verification that each A-h-k-a process a_i
- 15 is schedulable is performed by checking the condition that a_i 's latitude must be greater than or equal to its response time.

Two different methods of determining the response time of an A-h-k-a process will now be

20 described. The first method uses a formula to calculate the response time. The second method uses simulation to determine the response time. The second method gives tighter response times that can guarantee the schedulability of a larger number of cases, but requires

25 a longer computation time. The first method, while not as accurate as the second method, is faster. In practice time can be saved by applying the first method first, and only applying the second method if the response time of some A-h-k-a process determined by the

30 first method exceeds the latitude of that process.

"P-g" is the set of guaranteed periodic processes. In this step, P-g includes all the P-h-k processes, including those A-h-k-p processes that are translated into periodic processes. Later on, in Step 4, P-g is expanded to include all P-h-k and P-s-k processes.

The worst case response time of an A-h-k-a process a_i can be determined in accordance with the following method:

For all $a_i \in A\text{-h-k-a}$:

$$RE_{a_i} = c_{a_i} + \text{DelayA}(a_i, RE_{a_i}) + \text{DelayP}(a_i, RE_{a_i}) + B(a_i) + \text{GT}(a_i, RE_{a_i})$$

where

$$\text{DelayA}(a_i, RE_{a_i}) = \sum_{a_j \in A\text{-h-k-a} \wedge L_{a_j} \leq L_{a_i} \wedge j \neq i} \left\lceil \frac{RE_{a_i}}{\text{prd}_{a_j}} \right\rceil \cdot c_{a_j}$$

and

$$\text{DelayP}(a_i, RE_{a_i}) = \sum_{p_j \in P\text{-g} \wedge L_{p_j} \leq L_{a_i}} \left\lceil \frac{RE_{a_i}}{\text{prd}_{p_j}} \right\rceil \cdot c_{p_j}$$

and

$$B(a_i) = \max \{ c_{a_j}, e(p_l) - s(p_l) \mid (a_j \in A\text{-h-k-a} \wedge L_{a_j} > L_{a_i} \wedge \exists x_k, x_k \in A\text{-h-k-a} \vee x_k \in P\text{-g}: a_j \text{ excludes } x_k \wedge L_{x_k} \leq L_{a_i}) \vee (p_l \in P\text{-g} \wedge L_{p_l} > L_{a_i} \wedge \exists x_k, x_k \in A\text{-h-k-a} \vee x_k \in P\text{-g}: p_l \text{ excludes } x_k \wedge L_{x_k} \leq L_{a_i}) \}$$

and

$$\text{GT}(a_i, RE_{a_i}) = \sum_{p_l \in SG1(a_i)} \left\lceil \frac{RE_{a_i}}{\text{prd}_{p_l}} \right\rceil \cdot c_{a_i} + \sum_{p_l \in SG2(a_i)} \left\lceil \frac{RE_{a_i}}{\text{prd}_{p_l}} \right\rceil \cdot c_{a_i}$$

where $SG1(a_i) = \{p_l \mid p_l \in P\text{-g} \wedge L_{p_l} \leq L_{a_i} \wedge (a_i \text{ excludes } p_l)\};$
and $SG2(a_i) = \{p_l \mid p_l \in P\text{-g} \wedge L_{p_l} \leq L_{a_i} \wedge (\exists a_j \in A\text{-h-k-a}: a_i \text{ excludes } a_j \wedge L_{a_j} < L_{p_l})\};$

It should be noted that in the above method, the value of c_{pj} is the original computation time of p_j (it does not include the time reserved for A-h-k-a processes with less latitude).

In a first assumption, for each A-h-k-a process a_i , for each RE_{ai} computed by the above method, if $RE_{ai} \leq L_{ai}$, a_i will always meet its deadline at run-time.

The following procedure can be used to compute the worst case response time of each A-h-k-a process:

```

i:= 0;
failure= false;
while i ≤ number-of-A-h-k-a-processes and not(failure) do
begin
    if  $a_i \in$  A-h-k-a
    then
    begin
         $RE_{new_i} := c_{a_i}$ ;
        responsetimefound:= false;
        while not(responsetimefound) and not(failure) do
        begin
             $RE_{previous_i} := RE_{new_i}$ ;
             $RE_{new_i} = \text{DelayA}(a_i, RE_{previous_i}) + \text{DelayP}(a_i, RE_{previous_i})$ 
                 $+ B(a_i) + GT(a_i, RE_{previous_i})$ ;
            if  $RE_{previous_i} = RE_{new_i}$ 
            then
            begin
                 $RE_{a_i} := RE_{new_i}$ ;
                responsetimefound:= true;
            end
            if ( $RE_{new_i} > L_{a_i}$ )
            then failure:= true
        end;
    end;
    i:= i + 1;
end

```

Example 6

If the procedure and formula described in this specification is used to calculate the response times of the A-h-k-a processes in Examples 1-5 above, the following should be computed:

$$\begin{aligned}
RE_{a_0} &= c_{a_0} = 2 \leq L_{a_0} = 2 \\
RE_{a_1} &= c_{a_1} + \lceil RE_{a_1}/min_{a_0} \rceil c_{a_0} = 2 + \lceil 7/1000 \rceil 2 = 4 \leq L_{a_1} = 7 \\
DelayA(a_2, RE_{a_2}) &= \lceil RE_{a_2}/min_{a_0} \rceil c_{a_0} + \lceil RE_{a_2}/min_{a_1} \rceil c_{a_1} = 2 + 2 = 4 \\
DelayP(a_2, RE_{a_2}) &= \lceil RE_{a_2}/prd_{newp_3} \rceil c_{newp_3} + \lceil RE_{a_2}/prd_{p_4} \rceil c_{p_4} + \lceil RE_{a_2}/prd_{p_5} \rceil c_{p_5} \\
&\quad + \lceil RE_{a_2}/prd_{p_6} \rceil c_{p_6} + \lceil RE_{a_2}/prd_{p_7} \rceil c_{p_7} = 20 + 26 + 16 + 26 + 16 = 104 \\
B(a_2) &= c_{a_2} = 10 \\
GT(a_2, RE_{a_2}) &= \lceil RE_{a_2}/prd_{newp_3} \rceil c_{a_2} = 20 \\
RE_{a_2} &= c_{a_2} + DelayA(a_2, RE_{a_2}) + DelayP(a_2, RE_{a_2}) + B(a_2) + GT(a_2, RE_{a_2}) = 10 + \\
&\quad 4 + 104 + 10 + 20 = 148 \leq L_{a_2} = 239 \\
DelayA(a_9, RE_{a_9}) &= \lceil RE_{a_9}/min_{a_0} \rceil c_{a_0} + \lceil RE_{a_9}/min_{a_1} \rceil c_{a_1} + \lceil RE_{a_9}/min_{a_9} \rceil c_{a_9} = 2 + 2 \\
&\quad + 10 = 14 \\
DelayP(a_9, RE_{a_9}) &= \lceil RE_{a_9}/prd_{newp_3} \rceil c_{newp_3} + \lceil RE_{a_9}/prd_{p_4} \rceil c_{p_4} + \lceil RE_{a_9}/prd_{p_5} \rceil c_{p_5} \\
&\quad + \lceil RE_{a_9}/prd_{p_6} \rceil c_{p_6} + \lceil RE_{a_9}/prd_{p_7} \rceil c_{p_7} = 20 + 26 + 16 + 26 + 16 = 104 \\
B(a_9) &= 0 \\
GT(a_9, RE_{a_9}) &= 0 \\
RE_{a_9} &= c_{a_9} + DelayA(a_9, RE_{a_9}) + DelayP(a_9, RE_{a_9}) + B(a_9) + GT(a_9, RE_{a_9}) = 10 + \\
&\quad 14 + 104 = 128 \leq L_{a_9} = 259
\end{aligned}$$

25

Since the response time of every A-h-k-a process is less than or equal to its deadline, it is thus guaranteed that they are all schedulable.

Below, the second method which uses simulation will be described to determine the worst-case response time of an A-h-k-a process in a feasible pre-run-time

schedule of guaranteed periodic processes, which consists of an initial part of the pre-run-time schedule $S_{0(t_0)}$, which is a subschedule in the interval $(0, t_0)$; and a repeating part of the pre-run-time schedule

5 $S_{LCM}(prd_{LCM})$, which is a subschedule in the interval $(t_0, t_0 + prd_{LCM})$.

This method uses the functions of the A-h-k-a Scheduler and the Main Run-Time Scheduler, which are described in below in the section related to the run-

10 time phase.

A method for computing the worst case response time of an A-h-k-a process a_i in a feasible pre-run-time schedule of guaranteed periodic processes consisting of an initial part of the pre-run-time schedule $S_{0(t_0)}$, in

15 the interval $(0, t_0)$; and a repeating part of the pre-run-time schedule $S_{LCM}prd_{LCM}$, in the interval $(t_0, t_0 + prd_{LCM})$ follows:

fail:= false;

20 for $t_s := 0$ to $t_0 + prd_{LCM} - 1$ do
begin

For each A-h-k-a process a_b , such that $a_b \in A\text{-h-k-a} \wedge L_{ab} > L_{ai}$

$\wedge \exists x_k, x_k \in A\text{-h-k-a} \wedge x_k \in P\text{-g}: a_b \text{ excludes } x_k \wedge L_{xk}$

25 $=< L_{ai}$, do the following:

let a_b arrive at time $t_s - 1$, and use the A-h-k-a Scheduler and Main Run-Time Scheduler to schedule a_b and a_i to obtain a response time of a_i , called $RE_1(a_i, t_s, a_b)$, corresponding to each a_b according to the

30 assumptions (1)-(6) below, with the additional assumption that a_b can always start its execution at

end of its time slot in the pre-run-time schedule that was computed using adjusted computation times.

(1) a_i arrives in the system at time t_s .

- 5 (2) Unless a_i is delayed because of the conditions in Case 1 or Case 5 of the A-h-k-a Scheduler, (see (3) below), let every other A-h-k-a process a_j , such that $L_{a_j} \leq L_{a_i}$ arrive at the following instants in time:
 $R_{a_j}(k) = t_s + k \cdot \min_{a_j}$, $k = 0, 1, 2, \dots$ and
 10 be scheduled before a_i whenever a_i and a_j have both arrived and a_i has not yet started. If a_j is delayed by any of the conditions in Cases 1 - 7 of the A-h-k-a Scheduler, then let a_i be delayed by the same amount of time.

- 15 (All other A-h-k-a processes whose deadlines are shorter or equal to a_i 's deadline arrive at the same time as a_i at time t_s , and are put into execution before a_i .)

- (3) Whenever the conditions in Case 1 or Case 5 of the
 20 A-h-k-a Scheduler become true for a_i and some P-h-k process p at some time t , i.e.: if $\exists p, p \in P-g$:

P-g:

$$\begin{aligned} & s'(p) \geq t \wedge (a_i \text{ cannot be preempted by } p) \wedge L_{a_i} \geq L_p \\ & \wedge (\nexists p_l, p_l \in P-g: s(p_l) < s(p) < e(p) < e(p_l) \wedge L_{p_l} \leq L_{a_i}) \\ & \wedge (\nexists p_l, p_l \in P-g: s(p) < s(p_l) < e(p_l) < e(p) \wedge (a_i \text{ cannot be preempted by } p_l)) \\ & \wedge (\nexists p_m, p_m \in P-g: t < s'(p_m) \wedge e(p_m) \leq s(p) \wedge L_{a_i} < L_{p_m}) \\ & \wedge (e(p) - t) < c_{a_i} + \sum_{p_l \in P-g} \wedge t \leq s(p_l) < e(p) \wedge \neg(e'(p_l) \leq t) \wedge L_{p_l} \leq L_{a_i} c_{p_l} + \\ & \sum_{a_k \in A-h-k-a} \wedge d_{a_k} < d_p \wedge (\neg(0 \leq R'(a_k)) \vee (R'(a_k) \leq t \wedge \neg(e'(a_k) \leq t)) \vee (R'(a_k) + \min_{a_k} < e(p))) \\ & \left\lceil \frac{e(p) - t}{\min_{a_k}} \right\rceil \cdot c_{a_k} \end{aligned}$$

or

if $\exists p, p_1, p, p_1 \in P-g$:

$$\begin{aligned} & s'(p) \geq t \wedge s(p) < s(p_1) < e(p_1) < e(p) \wedge (a_i \text{ cannot be preempted by } p_1) \wedge \\ & L_{a_i} \geq L_p \end{aligned}$$

$$\begin{aligned}
& \wedge (\bar{A}p_m, p_m \in P-g: t < s'(p_m) \wedge e(p_m) \leq s(p) \wedge L_{a_i} < L_{p_m}) \\
& \wedge (s(p) - t) < c_{a_i} + \sum_{p_l \in P-g \wedge \neg(e'(p_l) \leq t) \wedge t \leq s(p_l) < e(p_l) \leq s(p)} c_{p_l} \\
& + \sum_{a_k \in A-h-k-a \wedge L_{a_k} < L_p \wedge (\neg(0 \leq R'(a_k)) \vee (R'(a_k) \leq t \wedge \neg(e'(a_k) \leq t)) \vee (R'(a_k) + \min_{a_k} < s(p)))} \\
& \left\lceil \frac{s(p) - t}{\min_{a_k}} \right\rceil \cdot c_{a_k}
\end{aligned}$$

Let t also be the earliest time that the conditions in Case 1 or Case 5 become true for that instance of p and a_i , then for every other A-h-k-a process a_j that belongs to the following set:

$$\begin{aligned}
& \{a_j | a_j \in A-h-k-a \wedge j \neq i \wedge L_{a_j} \leq L_{a_i} \wedge \\
& ((\neg(0 \leq R'(a_j)) \vee (R'(a_j) \leq t \wedge \neg(e'(a_j) \leq t)) \vee (R'(a_j) + \min_{a_j} < e(p))) \\
& \vee (s'(a_b) \leq t_s \wedge t - 1 \leq e'(a_b) \wedge s'(a_j) < t))\}
\end{aligned}$$

(a_j has a deadline that is shorter than or equal to a_i 's deadline and, either a_j has never arrived; or a_j has arrived but has not completed its computation; or a_j may arrive again before time $s(p)$; or at time $t - 1$ a_i was blocked by a_b and a_j started its execution before t), "delay" a_j 's arrival time to occur at time $s(p)$; if at time $s(p)$ the conditions in case 1 or Case 5 of the A-h-k-a Scheduler continue to be true for some other periodic process p' , then a_i should be delayed again, and the A-h-k processes a'_j that satisfy the conditions of the formula for p' should be delayed again until $s(p')$; otherwise a_j arrives at $s(p)$, and is scheduled before a_i ; and assume that p starts executing at time $s(p) + \sum_{a_k \in A-h-k-a \wedge L_{a_k} < L_p} C_{a_k}$.

computed, and the response time $RE_2(a_i, t_s)$ that assumed that no such a_b had arrived and blocked a_i has also been computed, set the response time of a_i with arrival time t_s , $RE(a_i, t_s)$ to be equal to the greatest among them,
 5 i.e., $RE(a_i, t_s) = \max\{RE_1(a_i, t_s, a_b), RE_2(a_i, t_s)\}$, and exit from the current iteration of the loop for this value of t_s , and start the next iteration for $t_s := t_s + 1$.

10 end;

if not fail then

$RE_{ai} := \max\{RE(a_i, t_s) \mid t_s = 0, 1, \dots, LCM - 1\}$

A description will be found below of scheduling
 15 of the A-h-k-a processes, of the A-h-k-a Scheduler and of definitions of the terms used above.

It is assumed in a second assumption that for each A-h-k-a process a_i , for each RE_{ai} determined in the above procedure, if $RE_{ai} \Rightarrow L_{ai}$, a_i will always meet its
 20 deadline at run-time.

Example 7

If the second method is used, that is, the
 25 simulation procedure above, to determine the response times of the A-h-k-a processes in Examples 1-6 above, the procedure will find the following.

RE_{a0} :

The maximum value of $RE(a_0, t_s)$ will occur when
 30 a_0 arrives at time $t_s = 0$. Since no process excludes a_0 , and a_0 has the minimum latitude among all processes, a_0

will always be put into execution immediately after it arrives, thus a_0 's response time $RE_{a_0} = RE(a_0, 0) = \max\{RE(a_0, t_s)\} = c_{a_0} = 2 \Rightarrow L_{a_0} = 2$.

5 RE_{a_1} :

The maximum value of $RE(a_1, t_s)$ will occur when a_1 arrives at time $t_s = 0$. Since no process excludes a_1 , and only one process a_0 has less latitude compared with a_1 's latitude, when a_1 arrives at time $t_s = 0$, assuming
 10 that a_0 will also arrive at time $t_s = 0$, a_1 will only be delayed by a_0 's execution time, thus a_1 's response time $RE_{a_1} = \max\{RE(a_1, t_s)\} = RE(a_1, 0) = c_{a_0} + c_{a_1} = 2 + 2 = 4 \Rightarrow L_{a_1} = 7$.

15 RE_{a_2} :

The maximum value of $RE(a_2, t_s)$ will occur when a_2 arrives at time $t_s = 82$ but a_9 arrived one time unit earlier at $t_s - 1 = 81$, so a_9 blocks a_2 at time 82. According to rule (2) in the simulation procedure, it is
 20 first assumed that a_0 and a_1 will also arrive at time $t_s = 82$, and will be put into execution from time 82 to 86, preempting a_9 . After a_0 and a_1 's completion, a_9 will resume at time 86 and complete its computation at time 95. At time 95, a_2 will be delayed by the conditions of
 25 Case 1 of the A-h-k-a Scheduler, because $e(newp_3) - t = 114 - 95 = 19 < c_{a_2} + c_{newp_3} = 10 + 10 = 20$. According to rule (3) in the simulation procedure, since at time 95 a_0 and a_1 belong to the set:

$$\{ a_j \mid a_j \in A\text{-h-k-a} \wedge j \neq i \wedge L_{a_j} \leq L_{a_i} \wedge$$

 30 $((\neg(0 \leq R'_{a_j})) \vee (R'_{a_j} \leq t \wedge \neg(e'_{a_j} \leq t)) \vee (R'_{a_j} + \min_{a_j} < e(p)))$

time 100 and execute from time 100 to 104; newp₃
 executes from time 104 to 114; As $L_{p_6} = 200 < L_{a_1} = 239$
 and $L_{p_7} = 200 < L_{a_2} = 239$,
 p₆ will execute from 114 to 140;
 5 p₇ will execute from 140 to 156;
 a₂ will execute from 156 to 166.
 Finally a₉ will execute from time 166 to 176. Thus a₉'s
 response time $RE_{a_9} = \max\{RE(a_9, t_s) = RE(a_9, 100) = e'(a_9)$
 $- R_{a_9} = 176 - 100 = 76 < L_{a_9} = 259$.

10 Since the response time of every A-h-k-a process
 is less than or equal to its deadline, it is possible to
 guarantee that they are all schedulable. Note that the
 response time of a₂ determined by the simulation
 procedure is 84 and is tighter than the response time of
 15 148 determined by the formula in the first method. The
 response time of a₉ determined by the simulation
 procedure is 76 and is also tighter than the response
 time of 128 determined by the formula in the first
 method.

20 In Example 1, none of the processes had offsets;
 consequently the length of the initial part of the pre-
 run-time schedule was 0. Below, another example is
 described which the periodic processes have offsets, and
 the initial part of the pre-run-time schedule is of non-
 25 zero length.

Example C

Suppose it is desired to schedule the same set
 of processes a_A, p_B, p_C, p_D given in Example A. The user
 30 can control the probability of each asynchronous process
 being converted into a periodic process or remaining

asynchronous, by setting the threshold values in the procedure for converting a set of asynchronous processes into periodic processes given earlier.

Assume that the value chosen for the threshold
5 for a_A was large and asynchronous process a_A was not converted into a new periodic process. The procedure for scheduling a set of periodic processes with offsets will construct the pre-run-time schedule for the processes p_B , p_C , p_D illustrated in Figure 19. Assuming
10 a_A is to be scheduled by the A-h-k-a Scheduler using the information in the pre-run-time schedule, the simulation procedure will determine that the worst case response time of a_A will happen when process a_A makes a request at time 6. At time 6, process a_A will be delayed by the
15 conditions in Case 1 of the A-h-k-a scheduling method. a_A will be executed from time 11 to time 13 after p_C has completed. The response time of process a_A is $RE(a_A, t_s) = RE(a_A, 6) = e'(a_A) - s'(a_A) = 13 - 6 = 7 \leq d_{aA} = 7$. In this case process a_A is also guaranteed to always meet
20 its deadline.

The simulation procedure above is more accurate than the method described earlier for determining the worst case response times of A-h-k-a processes, because the simulation procedure takes into account knowledge
25 about the positions of the periodic processes in the pre-run-time schedule. In contrast, the earlier formula does not take into account such knowledge, and assumes that in the worst case, all periodic processes may arrive at the same time. Note that currently, none of
30 the algorithms and protocols in the prior art that perform all scheduling activities at run-time, can

avoid making the latter overly pessimistic assumption in their schedulability tests.

If it is determined that the deadline of some hard deadline process cannot be met, that is, if a
5 feasible pre-run-time schedule does not exist for the given set of P-h-k processes, or if the response time of some A-h-k-a process exceeds its deadline, then one may have to modify the characteristics of or remove one or more P-h-k or A-h-k-a processes.

10 In the first case, the pre-run-time scheduling method will identify the critical set, that is, the subset of P-h-k processes for which either modifying the characteristics of one or more processes in that set, or removing one or more processes from that set is
15 necessary to meet the deadlines of all the P-h-k processes.

In the second case, the formula or simulation procedure for calculating the response time of each A-h-k-a process can be used to identify which processes
20 should be modified or removed, in order to meet the deadlines of all the A-h-k-a processes.

After the user has modified the characteristics of, or removed one or more P-h-k or A-h-k-a processes, the method will be applied again. The initial
25 determination and any subsequent modification of process characteristics by the user depends on the specific user application requirements and is outside the scope of this specification. This process must be repeated until there exists a feasible schedule for all
30 the hard-deadline processes.

Step 4: A feasible pre-run-time schedule for the P-s-k and P-h-k processes is constructed.

After guaranteeing the schedulability of all the processes

5 with hard deadlines, the set of periodic processes with soft deadlines and known characteristics (P-s-k processes) is scheduled together with the set of all periodic processes with hard deadlines and known characteristics (P-h-k processes), a feasible pre-run-
10 time schedule for these processes is constructed. Each P-s-k process is assigned an integer, called its "criticality level." Each P-s-k process is also assigned, in addition to its normal deadline, a "deadline upper-limit."

15 The computation times of the soft-deadline periodic P-s-k processes are modified in the same way as for the hard-deadline periodic P-h-k processes.

If it is determined that a feasible schedule does not exist, then the method will identify the soft
20 critical set, that is, the subset of soft-deadline processes for which either modifying the characteristics of one or more processes in that set, or removing one or more processes from that set, is necessary to meet the deadlines of all hard-deadline processes. The method
25 will select one process that has the lowest criticality level among the processes in the soft-critical set and increase the deadline of that process by an amount that does not exceed the deadline upper-limit of that process and attempt to find a feasible schedule again. The
30 deadline of the process with the lowest criticality level will be incremented until one of the following

happens: either a) a feasible schedule is found; or b) the previously selected process does not belong to the newly computed critical set; or c) the revised deadline of that process cannot be further increased without
5 exceeding the deadline upper-limit.

In the latter two cases, the method will select another process that has the lowest criticality level among all processes in the soft critical set and for which the deadline has not yet been revised, increment
10 its deadline, and attempt to find a feasible schedule again.

If it is determined that a feasible schedule still does not exist after the deadlines of all the processes in the soft critical set have been revised and
15 their deadline upper-limits have been reached, the method will provide the user with the list of soft-deadline processes in the soft critical set for which modifying the characteristics of one or more processes in that set or removing one or more processes in that
20 set is necessary to meet the deadlines of all hard-deadline processes.

After the user has modified the characteristics of one or more processes in the soft critical set, or removed one or more processes in that set, the method
25 will be applied again. The procedure will be repeated until there exists a feasible schedule for all the P-h-k and P-s-k processes. Again, the initial determination and any subsequent modification of process characteristics by the user depends on the specific user
30 application requirements and is outside the scope of this specification.

their deadline upper-limits have been reached, the method will provide the user with the list of soft-deadline processes in the set that contribute to a_i 's worst-case response time for which modifying the

5 characteristics of one or more processes in that set or removing one or more processes in that set is necessary to meet the deadlines of all the A-h-k-a processes.

After the user has modified the characteristics of one or more processes that contribute to a_i 's worst-

10 case response time, or removed one or more processes in that set, the method will be applied again. The procedure should be repeated until the worst-case response time of every A-h-k-a process is less than or equal to its deadline.

15 At the end of Step 4 the method will generate a feasible pre-run-time schedule for all the P-h-k, and P-s-k processes, while guaranteeing that the response times of all the A-h-k-a processes will be less than or equal to their deadlines.

20 The set of P-h-k and P-s-k processes will be referred to as the set of guaranteed periodic processes. A simplified procedure for implementing Step 4 will be described later.

25 Example 8

Assume that in addition to the hard deadline processes described in Examples 1-7 above, the following periodic process has a soft deadline and known

30 characteristics (P-s-k process):

$p_8: R_{p_8} = 20, c_{p_8} = 16, d_{p_8} = 55, prd_{p_8} = 200;$

Assume further that p_8 's criticality is 3, its deadline upperlimit is 100.

p_8 's adjusted computation time is:

$$5 \quad c_{p_8}' = c_{p_8} + ca_0 + ca_1 = 16 + 2 + 2 = 20.$$

Firstly it will be determined that no feasible schedule exists for the given set of process parameters. The optimal schedule for the given set of parameters is the same as the schedule shown in Figure 3, except that
 10 $d_{p_8} = 55$ and p_8 is late by 5 time units. The soft critical set contains one process p_8 . The simplified procedure for Step 4 referred to above will increase the deadline of p_8 until $d_{p_8}' = 60$, at which point the feasible schedule of the P-h-k and P-s-k processes is
 15 obtained, as shown in Figure 3.

If the formula in the first method is used to calculate the response times of the A-h-k-a processes the following is obtained:

$$\begin{aligned} RE_{a_0}, RE_{a_1} &\text{ remain the same as in Step 3, and are less than } L_{a_0} \text{ and } L_{a_1} \text{ respectively.} \\ \text{DelayA}(a_2, RE_{a_2}) &= \lceil RE_{a_2}/min_{a_0} \rceil c_{a_0} + \lceil RE_{a_2}/min_{a_1} \rceil c_{a_1} = 2 + 2 = 4 \\ \text{DelayP}(a_2, RE_{a_2}) &= \lceil RE_{a_2}/prd_{newp_3} \rceil c_{newp_3} + \lceil RE_{a_2}/prd_{p_4} \rceil c_{p_4} + \lceil RE_{a_2}/prd_{p_5} \rceil c_{p_5} \\ &\quad + \lceil RE_{a_2}/prd_{p_6} \rceil c_{p_6} + \lceil RE_{a_2}/prd_{p_7} \rceil c_{p_7} + \lceil RE_{a_2}/prd_{p_8} \rceil c_{p_8} \\ &= 20 + 26 + 16 + 26 + 16 + 16 = 120 \\ B(a_2) &= c_{a_9} = 10; \\ GT(a_2, RE_{a_2}) &= \lceil RE_{a_2}/prd_{newp_3} \rceil c_{a_2} = 20 \\ RE_{a_2} &= c_{a_2} + \text{DelayA}(a_2, RE_{a_2}) + \text{DelayP}(a_2, RE_{a_2}) + B(a_2) + GT(a_2, RE_{a_2}) = 10 + \\ &\quad 4 + 120 + 10 + 20 = 164 \leq L_{a_2} = 239 \\ \text{DelayA}(a_9, RE_{a_9}) &= \lceil RE_{a_9}/min_{a_0} \rceil c_{a_0} + \lceil RE_{a_9}/min_{a_1} \rceil c_{a_1} + \lceil RE_{a_9}/min_{a_2} \rceil c_{a_2} = 2 + 2 \\ &\quad + 10 = 14 \end{aligned}$$

$$\begin{aligned}
\text{DelayP}(a_9, RE_{a_9}) &= \lceil RE_{a_9}/prd_{newp_3} \rceil c_{newp_3} + \lceil RE_{a_9}/prd_{p_4} \rceil c_{p_4} + \lceil RE_{a_9}/prd_{p_5} \rceil c_{p_5} \\
&+ \lceil RE_{a_9}/prd_{p_6} \rceil c_{p_6} + \lceil RE_{a_9}/prd_{p_7} \rceil c_{p_7} + \lceil RE_{a_9}/prd_{p_8} \rceil c_{p_8} \\
&= 20 + 26 + 16 + 26 + 16 + 16 = 120 \\
B(a_9) &= 0; \\
GT(a_9, RE_{a_9}) &= 0; \\
RE_{a_9} &= c_{a_9} + \text{DelayA}(a_9, RE_{a_9}) + \text{DelayP}(a_9, RE_{a_9}) + B(a_9) + GT(a_9, RE_{a_9}) = 10 + \\
14 + 120 &= 144 \leq L_{a_9} = 239
\end{aligned}$$

If the second method is used, that is, the simulation procedure described above, to calculate the response times of the A-h-k-a processes in the examples above, the procedure will find the following:

- 10 a_0 's response time RE_{a_0} and a_1 's response time RE_{a_1} will remain the same as in Example 6, that is:
- $$RE_{a_0} = RE(a_0, 0) = \max\{RE(a_0, t_s)\} = c_{a_0} = 2 \leq d_{a_0} = 2.$$
- $$RE_{a_1} = \max\{RE_{a_1}, t_s\} = RE(a_1, 0) = c_{a_0} + c_{a_1} = 2 + 2 = 4 \leq d_{a_1} = 7.$$

- 15 RE_{a_2} :

The maximum value of $RE(a_2, t_s)$ will happen when a_2 arrives at time $t_s = 182$ but a_9 arrived one time unit earlier at $t_s - 1 = 181$, so a_9 blocks a_2 at time 182.

- According to rule (2) in the simulation procedure, it is first assumed that a_0 and a_1 will also arrive at time $t_s = 182$, and will be put into execution from time 182 to 186, preempting a_9 . After a_0 and a_1 's completion, a_9 will resume at time 186 and complete its computation at time 195. At time 195, a_2 will be delayed
- 20 by the conditions of Case 1 of the A-h-k-a Scheduler, because $e(newp_3 - t) = 214 - 195 = 19 < c_{a_2} + c_{newp_3} = 10 + 10 = 20$.

- According to rule (3) in the simulation procedure, since at time 195 a_0 and a_1 belong to the
- 30 set:

$\{a_j | a_j \in A\text{-h-k-a} \wedge j \neq i \wedge L_{a_j} \leq L_{a_i} \wedge$
 $((\neg(0 \leq R'(a_j)) \vee (R'(a_j) \leq t \wedge \neg(e'(a_j) \leq t)) \vee (R'(a_j) + \min_{a_j} < e(p)))$
 $\vee (s'(a_b) \leq t_s \wedge t-1 \leq e'(a_b) \wedge s'(a_j) < t))\}$
 because $a_0 \in A\text{-h-k-a} \wedge a_0 \neq a_2 \wedge L_{a_0} \leq L_{a_2} \wedge (s'(a_0) \leq t_s = 182 \wedge t-1 = 195-1 =$
 $194 \leq e'(a_0) = 195 \wedge s'(a_0) = 182 < t = 195.$

(at time $t-1 = 195-1 = 194$ a_2 was blocked by
 a_9 (" a_b ") and a_0 (" a_j ") started its execution before $t =$
 195). a_1 also meets the above conditions similar to a_0 .

- 10 According to rule (3) in the simulation
 procedure, a_0 and a_1 's arrival times are "delayed" to
 occur at time $s(\text{newp}_3) = 200$ and are scheduled before a_2
 to execute from time 200 to 204; newp_3 starts executing
 at time $s(\text{newp}_3) + c_{a_0} + c_{a_1} = 200 + 2 + 2 = 204$, and
 15 completes its execution at time 214;
 a_2 starts at time 214 and executes until time 220.
 As $L_{p_8} = d_{p_8}' - r_{p_8} = 260 - 220 = 40 < L_{a_2} = d_{a_2} = 239$, L_{p_5}
 $= d_{p_5} - r_{p_5} = 250 - 230 = 20 < L_{a_2} = d_{a_2} = 239$,
 and $L_{p_4} = d_{p_4} - r_{p_4} = 200 - 0 = 200 < L_{a_2} = d_{a_2} = 239$;
 20 p_8 will preempt a_2 at time 220;
 p_8, p_5, p_4 will execute from time 220 to 278;
 a_2 will resume execution from time 278 to 282;
 Thus a_2 's response time $RE_{a_2} = \max\{RE(a_2, t_s)\} = RE(a_2,$
 $182) = e'(a_2) - R_{a_2} = 282 - 182 = 100 < L_{a_2} = 239.$

- 25 Figure 4 illustrates a possible run-time
 executionn of the A-h-k-a processes a_0, a_1, a_2, a_9 ,
 together with the P-h-k and P-s-k processes of Figure 3.
 The worst case response time of the A-h-k-a process a_2
 is $RE_{a_2} = \max\{RE(a_2, t_s)\} = RE(a_2, 182) = e'(a_2) - R_{a_2} = 282$
 30 $- 182 = 100$, as computed in step 4.

response time of 144 determined by the formula in the first method.

Fig. 3 illustrates the feasible pre-run-time schedule in which each guaranteed periodic process reserves a time frame that includes reserved processor capacity for any A-h-k-a process that has a shorter deadline than that guaranteed periodic process's deadline.

Step 5: Determine the response times of the A-s-k processes

A-s-k processes are scheduled at run-time by the Main Run-Time Scheduler, but their worst-case response times are determined before run-time in this step. A-s-k processes are scheduled at a lower priority than the A-h-k-a, P-h-k, P-s-k processes. That is, A-s-k processes are executed only when there does not exist any A-h-k-a, P-h-k, or P-s-k process that is ready for execution. If more than one A-s-k process are competing for execution, the process with the shortest deadline will be chosen for execution.

An A-s-k process is not allowed to have any precedence relation with any other process. An A-s-k process a_i is also not allowed to have any exclusion relation of the form a_i excludes x where x is an A-h-k-a, P-h-k, or P-s-k process. These restrictions are imposed in order to prevent A-s-k processes from causing any delay to A-h-k-a, P-h-k, or P-s-k processes, so that one can guarantee that all the hard deadlines will be satisfied, and also provide firm response time

guarantees for all the processes with known characteristics.

Two different methods of determining the worst-case

5 response time of an A-s-k process will now be described.

The first method uses a mathematical formula to calculate the response time, and is very similar to the formula described in Step 3 for determining the worst-case response time of an A-h-k-a process, except that:

10 (a) all A-h-k-a, P-h-k and P-s-k processes have higher priority than any A-s-k process a_i , so their execution times are included together with the execution times of A-s-k processes that have shorter deadlines than a_i in the terms $\text{Delay}(a_i, RE_{ai})$ and $\text{Delay}(a_i, RE_{ai})$;

15 (b) because an A-s-k process cannot exclude a P-h-k, P-s-k, or

A-h-k-a process, the term $GT(a_i, RE_{ai})$ is not required in the formula; and (c) the term $B(a_i)$ only needs to

20 consider the blocking time due to A-s-k processes that have greater deadlines than a_i . Because the rest of the formula in Step 3 is basically the same as the formula used here, to avoid repetition, the complete definition of the formula used here is provided

in Appendix 3.

25

Example 9

Assume the following asynchronous process with a soft deadline and known characteristics (A-s-k process):

30

$a_{10}: c_{a_{10}} = 10, d_{a_{10}} = 300, \min_{a_{10}} = 300.$

The procedure to be described below for
determining the response times of the A-s-k processes is
used to determine the response time of the A-s-k process
5 a_{10} , the following will be processed:

$$\text{DelayA}(a_{10}, RE_{a_{10}}) = \lceil RE_{a_{10}} / \min_{a_0} \rceil c_{a_0} + \lceil RE_{a_{10}} / \min_{a_1} \rceil c_{a_1} + \lceil RE_{a_{10}} / \min_{a_2} \rceil c_{a_2} \\ + \lceil RE_{a_{10}} / \min_{a_9} \rceil c_{a_9} = 2 + 2 + 10 + 10 = 24$$

$$\text{DelayP}(a_{10}, RE_{a_{10}}) = \lceil RE_{a_{10}} / \text{prd}_{\text{newp}_3} \rceil c_{\text{newp}_3} + \lceil RE_{a_{10}} / \text{prd}_{p_4} \rceil c_{p_4} + \lceil RE_{a_{10}} / \text{prd}_{p_5} \rceil c_{p_5} \\ + \lceil RE_{a_{10}} / \text{prd}_{p_6} \rceil c_{p_6} + \lceil RE_{a_{10}} / \text{prd}_{p_7} \rceil c_{p_7} + \lceil RE_{a_{10}} / \text{prd}_{p_8} \rceil c_{p_8} = 20 + 26 + 16 + 26 + 16 \\ + 16 = 120$$

$$B(a_{10}) = 0$$

$$RE_{a_{10}} = c_{a_{10}} + \text{DelayA}(a_{10}, RE_{a_{10}}) + \text{DelayP}(a_{10}, RE_{a_{10}}) = 10 + 24 + 120 = 154 \\ \leq L_{a_{10}} = 300$$

The second method uses a simulation procedure to
15 determine the worst-case response time of each A-s-k
process. The simulation procedure used here is also
very similar to the simulation procedure described in
Step 3 for determining the worst-case response time of
an A-h-k-a process, except that,
20 (a) because all A-h-k-a processes have higher priority
than any A-s-k process a_i , they are all assumed to
arrive at the same time as a_i , together with all A-s-k
processes that have shorter deadlines compared with a_i ;
(b) because an A-s-k process cannot exclude a P-h-k, P-
25 s-k or A-h-k-a process, there is no need for an A-s-k
process to avoid blocking a P-h-k, P-s-k or A-h-k-a
process such as in Case 1 and Case 5 of the A-h-k-a
Scheduler; consequently there is no need for a rule in
the simulation procedure for A-s-k processes that is
30 similar to the rule (5) in the simulation procedure in
Step 3.

Because the rest of the simulation procedure in Step 3 is basically the same as the simulation procedure used here, to avoid repetition, the complete description of the simulation procedure used here is given later in this specification.

Similar to the case in Step 3, compared with the formula, the simulation procedure gives tighter response times that can guarantee the schedulability of a larger number of cases, but requires a longer computation time.

The simulation procedure used here also uses the functions of the A-h-k-a Scheduler and the Main Run-Time Scheduler, which are described later.

Example 10

This example is a description of the use of this simulation procedure. Assume that the second method, that is, the simulation procedure described later, is used to calculate the worst-case response time of the A-s-k process a_{10} in Example 9 above, the procedure will find the following:

The maximum value of $RE(a_{10}, t_s)$ will happen when a_{10} arrives at time $t_s = 196$. Figure 5 is an illustration of this case, a run-time execution of the A-s-k process a_{10} , together with the A-h-k-a processes a_0, a_1, a_2, a_9 , and the P-h-k and P-s-k processes of Figure 3. The simulation procedure simulates this execution in which the worst case response time of a_{10} , $RE_{a_{10}} = \max\{RE(a_{10}, t_s)\} = RE(a_{10}, 196) = e'(a_{10}) - R_{a_{10}} = 298 - 196 = 102$, as determined in Example 10, step 5.

At time 196, the simulation procedure assumes that a_0, a_1, a_2, a_9 will arrive at the same time as a_{10} , so a_0 will execute from time 196 to 198, and a_1 will execute from time 198 to 200. $newp_3$ will execute from
5 time 200 to 210. a_2 will execute from time 210 to 220. p_8, p_5, p_4 will execute from time 220 to time 278. a_9 will execute from time 278 to 288.

a_{10} will execute from time 288 to 298. Thus a_{10} 's worst-case response time will be $RE_{a_{10}} = \max\{RE(a_{10}, t_s)\}$
10 $= RE(a_{10}, 196) = e'(a_{10}) - R_{a_{10}} = 298 - 196 = 102 < L_{a_{10}} = 300$.

Run-Time Phase

15 During run-time, the processor capacity that is left unused by guaranteed periodic processes (the set of P-h-k and P-s-k processes P-g) in the pre-run-time schedule generated in Step 4 will be used to schedule the
20 processes that are asynchronous and for which the characteristics are either known before run-time (A-s-k and A-h-k-a processes) or unknown before run-time but known as soon as the process arrives in the system (A-s-u processes).

25 In the previous step, a time slot in the feasible pre-run-time schedule was reserved for each guaranteed periodic process. However, at run-time each periodic process may not necessarily execute within its time slot in a pre-run-time schedule, because provided
30 that it can be guaranteed that all the constraints will be satisfied, it is preferred that each process should

be executed as early as possible at run-time, in order to minimize the response times. Nevertheless, the beginning and end times of the time slots are important parameters that will be used by the run-time scheduler
5 to determine, at each point in time, whether each asynchronous or periodic process can be safely put into execution while guaranteeing that all the constraints will be satisfied.

In particular, the run-time scheduler will
10 always guarantee that,
(1) the actual execution order of each pair of "guaranteed" periodic processes p_1 and p_2 will be the same as the relative ordering of their time slots in the pre-run-time schedule, that is, if $e(p_1) \leq s(p_2)$, then
15 $e'(p_1) \leq s'(p_2)$; and
(2) the actual completion time $e'(p)$ of each "guaranteed" periodic process p will never exceed the end of p 's time slot $e(p)$ in the pre-run-time schedule.

20 Scheduling A-h-k-a Processes

Each time the Run-Time Scheduler is executed, it will first try to schedule A-h-k-a processes according to the procedure below.

25 For any A-h-k-a process a_i and any P-g process p_1 , the following should hold:

a_i should not be able to be preempted by p_1 , if the following conditions hold:

(a_i excludes $p_1 \vee (\exists a_j, a_j \in \text{A-h-k-a}: L_{a_j} < L_{p_1} \wedge a_i$
30 excludes $a_j)$

Simplified A-h-k-a Scheduler Method

The A-h-k-a Scheduler Method functions as part of the

5 Main-Run-Time Scheduler to be described below.

A-h-k-a-Scheduler:

At any time t:

if some A-h-k-a process a_i has arrived at time t,
or if some process x_i completes its computation at time

10 t

or if t is both the release time and start time in the
pre-run-time schedule for some P-g process p, i.e., t =

$R_p = s(p)$

then

15 begin

for each A-h-k-a process a_i that has already
arrived and not yet completed,

i.e., $R'(a_i) \leq t \wedge \neg(e'(a_i) \leq t)$, if a_i
satisfies any of the following conditions,

20 then Delay a_i :

Case 1:

if $\exists p, p \in P\text{-g}$:

$s'(p) \geq t \wedge (a_i \text{ cannot be preempted by } p) \wedge L_{a_i} \geq L_p$

$\wedge (\nexists p_l, p_l \in P\text{-g}: s(p_l) < s(p) < e(p) < e(p_l) \wedge L_{p_l} \leq L_{a_i})$

$\wedge (\nexists p_l, p_l \in P\text{-g}: s(p) < s(p_l) < e(p_l) < e(p) \wedge (a_i \text{ cannot be preempted by } p_l))$

$\wedge (\nexists p_m, p_m \in P\text{-g}: t < s'(p_m) \wedge e(p_m) \leq s(p) \wedge L_{a_i} < L_{p_m})$

$\wedge (e(p) - t) < c_{a_i} + \sum_{p_l \in P\text{-g} \wedge t \leq s(p_l) < e(p) \wedge \neg(e'(p_l) \leq t) \wedge L_{p_l} \leq L_{a_i}} c_{p_l} +$

$\sum_{a_k \in A\text{-h-k-a} \wedge L_{a_k} < L_p \wedge (\neg(0 \leq R'(a_k)) \vee (R'(a_k) \leq t \wedge \neg(e'(a_k) \leq t)) \vee (R'(a_k) + \min_{a_k} < e(p)))} \lceil \frac{e(p) - t}{\min_{a_k}} \rceil \cdot c_{a_k}$

then Delay a_i ;

In Case 1: a_i is delayed either if there exists the possibility that the immediate execution of a_i may cause a P-g process p with less latitude to be delayed (as shown in Figure 20A); or, if there exists the

5 possibility that it may cause some A-h-k-a process a_j to be blocked for the duration of two processes a_i and p which both have greater latitude compared with a_j 's latitude (as shown in Figure 20B).

10 Case 2:

As shown in Figure 20C,

if $\exists x, x \in P-g \vee x \in A-h-k-a$:

$s'(x) < t \wedge \neg(e'(x) \leq t) \wedge x$ excludes a_i then Delay a_i ;

15 In Case 2: a_i is delayed because it is not allowed to preempt any process x that excludes a_i .

Case 3:

As shown in Figure 20D,

20 if $\exists x, x \in P-g \vee x \in A-h-k-a$:

$s'(x) < t \wedge \neg(e'(x) \leq t) \wedge L_x \leq L_{a_i}$
then Delay a_i ;

In Case 3: a_i is delayed because it is not allowed to preempt any process x that has less or the

25 same latitude as a_i .

Case 4:

As shown in Figure 20E,

if $\exists a_j, p, a_j \in A-h-k-a, p \in P-g$:

30 $s'(p) \Rightarrow t \wedge s'(a_j) < t \wedge \neg(e'(a_j) \leq t)$

then Delay a_i .

In Case 6: a_i is delayed because it is not allowed to preempt any process x that excludes some other A-h-k-a process a_j which has a latitude that is less than both x and a_i 's latitude, because that may cause a_j to be blocked by the duration of more than one process with greater latitude.

Case 7:

10 As shown in Figure 20H,

if $\exists p, p \in P-g$:

$R_p \leq t \wedge (e'(p) \leq t) \wedge L_p \leq L_{a_i}$

$\wedge (s'(a_i) < t \wedge (a_i \text{ cannot be preempted by } p))$

$\wedge \text{not} \exists p_i, p_i \in P-g: s(p_i) \leq s(p) \wedge (e'(p_i) \leq t)$

15 $\wedge (s(p_i) \leq s(p) \wedge e(p) < e(p_i))$

then Delay a_i ;

In Case 7: a_i is delayed so that it can be preempted by a P-g process p that has a latitude that is less than or equal to a_i 's latitude, when a_i does not exclude p and does not exclude any A-h-k-a process with a latitude that is shorter than p 's latitude, and there does not exist any P-g process p_i that has not completed such that p_i is ordered before p and p does not preempt p_i in the pre-run-time schedule.

25

Select, among all processes $a_i \in A-h-k-a$, such that a_i has already arrived and not yet completed, and a_i is NOT Delayed, the process which has the least latitude. If more than one process is thus selected,

select among them the process that has the smallest index.

end;

5

return to Main Run-Time Scheduler.

The A-h-k-a Scheduler has the following properties:

10 Property 1. Each P-g process p 's execution can only be delayed by A-h-k-a processes that have less latitude than p 's latitude. A P-g process will never be delayed by any A-h-k-a process that has a greater or equal latitude.

15

Property 2. Any A-h-k-a process a_i cannot be blocked by more than one critical section belonging to A-h-k-a processes that have deadlines greater than a_i 's deadline.

20

Property 3. No deadlocks can ever occur.

Property 4. Each P-g process p will always be completed on or before $e(p)$, that is, the end of the time slot
25 allocated to p in the pre-run-time schedule.

Example 11

Continuing with the set of processes in Examples 1-10 above, assume that A-h-k-a process a_2 makes a
30 request at time 99. Figure 6 is an illustration of this case, which is a possible run-time execution of the A-h-

schedule in order to avoid any excessive delay of an A-h-k-a process a_i that may be caused by preemptions of a P-g process's critical section by other P-g processes.

Above, A P-g process p_1 has been allowed to be
5 preempted by some other P-g process p_2 , even if this may cause some A-h-k-a process a to be blocked by the duration of two critical sections belonging to two P-g processes p_1 and p_2 which both have latitudes that are greater than a 's latitude. This provides greater
10 flexibility to the scheduling of P-g processes. However, it is easy to guarantee that any A-h-k-a process a cannot be blocked by the duration of two critical sections belonging to two P-g processes p_1 and p_2 which both have latitudes that are greater than a 's
15 latitude. To guarantee this, all one needs to do is the following, for all pairs of P-g processes p_1 and p_2 , if p_1 excludes some A-h-k-a process a , and $L_{p(2)} \Rightarrow L_a$, then add the exclusion relation p_1 excludes p_2 .

If the potential run-time overhead of the A-h-k-a
20 a Scheduler in the integration approach is compared with the overhead of methods that schedule all the tasks at run-time, the following may be noticed:

(a) With the integration approach, the number of
processes
25 that the A-h-k-a Scheduler needs to handle, should be very small. This is because, in most real-time systems, it has been observed that the bulk of the computation is performed by periodic processes, while the number of asynchronous processes with hard deadlines is usually
30 very small. In addition a significant portion of the

asynchronous processes will be transformed into periodic processes when using this approach.

(b) The interarrival times of A-h-k-a processes that are not converted into new P-h-k processes are likely to be
5 long.

(c) A significant portion of the parameters used by the A-h-k-a Scheduler to make scheduling decisions, are known before run-time, so one can pre-compute major portions of the conditions that are used for decision
10 making, hence the amount of computation that needs to be performed for scheduling purposes at run-time can be minimized.

Thus the run-time overhead of the A-h-k-a Scheduler is believed to be far smaller than the
15 overhead of methods that schedule all the tasks at run-time.

The Main Run-Time Scheduler

20 At run-time, the order of the execution of any pair of guaranteed periodic processes, i.e., P-h-k or P-s-k processes is kept consistent with the order of that pair of processes in the pre-run-time schedule.

A-s-u processes are scheduled at a lower
25 priority than the A-h-k-a, P-h-k, P-s-k, and A-s-k processes. That is, A-s-u processes are executed only when there does not exist any process with known characteristics, i.e., A-h-k-a, P-h-k, P-s-k, or A-s-k process, that is ready for execution. If more than one
30 A-s-u process are competing for execution, the process with the shortest deadline will be chosen for execution.

{there exists p that has started and has not
 completed, and there does not exist any other p_i that is
 ready and has not completed, such that P_i 's time slot is
 nested within p's time slot in the pre-run-time
 5 schedule}
 then continue to execute p.
 else
 if $\exists p, p \in P-g: R_p \leq t \wedge \neg(e'(p) \leq t)$
 $\wedge \text{not} \exists p_i, p_i \in P-g: \neg(e'(p_i) \leq t) \wedge s(p_i) \leq$
 10 $s(p) \wedge \neg(s(p_i) \leq s(p) \wedge e(p) < e(p_i))$
 $\wedge \text{not} \exists p_j, p_j \in P-g: R_{p_j} \leq t \wedge \neg(e'p_j) \leq t) \wedge$
 $s(p) < s(p_j) \wedge e(p_j) < e(p)$
 {there exists p that is ready and has not
 completed, and there does not exist any other p_i that
 15 has not yet completed, such that p_i is ordered before p
 in the pre-run-time schedule, and p's time slot is not
 nested within p_i 's time slot in the pre-run-time
 schedule, and there does not exist any other p_j that is
 ready and has not completed, such that p_j 's time slot is
 20 nested within p's time slot in the pre-run-time
 schedule}
 then execute p
 else
 if $\exists a_i, a_i \in A-s-k: R_{a_i} \leq t \wedge \neg(e'(a_i) \leq t)$
 25 $\wedge \text{not} \exists x: (s'(x) < t \wedge \neg(e'(x) \leq t) \wedge ((x$
 excludes $a_i)$
 $\vee (\exists a_j, a_j \in A-s-k: s'(x) < t \wedge \neg(e'(x) \leq t) \wedge x$
 excludes a_j
 $\wedge L_{a_j} < L_x$
 30 $\wedge L_{a_j} < L_{a_i}))$

{there exists A-s-k process a_i that is ready and
 has not completed, and there does not exist any other
 process x such that x excludes a_i or x excludes some
 process a_j such that a_j has a latitude that is less than
 5 both x 's and a_i 's latitude, and x has started but not
 completed}
 then select among them, a process a_i that has the
 shortest deadline;
 if among such processes there are some that have
 10 already started, then choose a process that has already
 started; and execute a_i ;
 else
 if $\exists a_i, a_i \in A-s-u: R_{ai} \leq t \wedge \neg(e'(a_i) \leq t)$
 $\wedge \text{not} \exists x: (s'(x) < t \wedge \neg(e'(x) \leq t \wedge ((x$
 15 excludes $a_i)$
 $\vee (\text{exists } a_j, a_j \in \text{In } A-s-u: s'(x) < t \wedge \neg(e'(x)$
 $\leq t) \wedge x \text{ excludes } a_j$
 $\wedge L_{aj} < L_x$
 $\wedge L_{aj} < L_{ai}$
 20 {there exists A-s-u process a_i that is ready and
 has not completed, and there does not exist any other
 process x such that x excludes a_i or x excludes some
 process a_j such that a_j has a latitude that is less than
 both x 's and a_i 's latitude, and x has started but not
 25 completed then select among them, a process a_i that has
 the shortest deadline; if among such processes there are
 some that have already started, then choose a process
 that has already started; and execute a_i ;
 end;

30

Example 12

Continuing with the set of processes in Examples 1-11 above, assume the following asynchronous process
5 a_{11} with a soft deadline and unknown characteristics (A-s-u process). (a_{11} 's characteristics are only known after its arrival.)

a_{11} : $c_{a_{11}} = 10$, $d_{a_{11}} = 300$.

10

Assume also that A-s-u process a_{11} makes a request at time 190; A-h-k-a process a_2 makes a request at time 191; A-s-k process a_{10} makes a request at time 196; and A-h-k-a processes a_0 and a_1 make requests at
15 time 200. Figure 7 illustrates an example of this case, in particular a run-time execution of the A-s-u process a_{11} , and the A-s-k process a_{10} , scheduled during main run-time scheduling together with the A-h-k-a processes a_0 , a_1 , a_2 and the P-h-k and P-s-k processes described
20 with regard to Figure 3, in Example 12, during the run-time phase.

At time 190 a_{11} will be put into execution as there are no other processes that are ready for execution. At time 191 a_2 will be delayed because the
25 conditions of Case 1 of the A-h-k-a Scheduler will be true. Note that a_2 excludes $newp_3$, and $L_{newp_3} < L_{a_2}$; if a_2 is allowed to execute at time 191, it will cause $newp_3$ to miss its deadline if a_0 and a_1 also preempt $newp_3$. At time 196 a_{10} will preempt a_{11} as A-s-k processes are
30 scheduled before A-s-u processes. At time 200 a_0 will

preempt a_{10} as A-h-k-a processes are scheduled before A-s-k processes.

a_{11} will execute from time 190 to 196; a_{10} will execute from time 196 to 200; a_0 will execute from time 200 to 202; a_1 will execute from time 202 to 204; $newp_3$ will execute from time 204 to 214. As $L_{p_8} < L_{a_2}$, $L_{p_5} < L_{a_2}$, and $L_{p_4} < L_{a_2}$; p_8 will preempt a_2 at time 220; p_8 , p_5 , p_4 will execute from time 220 to 278; a_2 will resume execution from time 278 to 282; a_{10} will resume execution from time 282 to 288; a_{11} will resume execution from time 288 to 292.

Note that each process may be completed earlier than the time indicated in the pre-run-time schedule, since the time that is reserved for each synchronous process with a shorter deadline in a guaranteed periodic process's time frame in the pre-run-time schedule will not be used by that asynchronous process if it does not arrive during that time frame.

Example 13

In example 3, when using the procedure for converting a set of asynchronous processes into a set of new periodic processes, $threshold(a_3)$ was set to 2.5, resulting in the A-h-k process a_3 being converted into a new process $newp_3$.

Now assume that $threshold(a_3)$ is set to an arbitrary large value, say 50, that would guarantee that a_3 would not be converted into a periodic process.

In the case that A-h-k process a_3 remains asynchronous, because the latitude of a_3 , $L_{a_3} = d_{a_3} =$

times of all the other asynchronous processes are all less than or equal to their respective deadlines, as shown in Figure 8.

The embodiments described herein are
5 advantageous methods of the integration approach compared with methods that perform all scheduling activities at run-time. It should be noted that existing methods or protocols that perform all scheduling activities at run-time are not able to
10 guarantee the schedulability of the set of processes given in these examples.

There are many reasons for this, including:

1. Prior art run-time scheduling methods are not capable of finding optimal schedules involving critical
15 sections, except for the simplest problem instances, because not enough time is available to the scheduler at run-time.
2. Prior art run-time scheduling methods cannot handle precedence
20 constraints, release time and exclusion constraints simultaneously in an efficient way.
3. Current run-time scheduling methods are unable to take full advantage of the knowledge about processes characteristics that is available before run-time. For
25 example, no prior art run-time scheduling method can completely avoid blocking of a periodic process with less latitude by a asynchronous process with greater latitude, which the integration method described herein is capable of doing, as shown in the examples above. As
30 another example, when determining the worst-case response times of asynchronous processes, no prior art

run-time scheduling method can completely avoid making the overly pessimistic assumption that, for each process, all the periodic processes with shorter deadlines can arrive at the same time to delay that
5 process. In contrast, the integration method in accordance with the present invention can avoid making such an overly pessimistic assumption, as shown in the examples where a simulation procedure can obtain tighter worst-case response times for asynchronous processes, by
10 taking advantage of the knowledge of the positions of the periodic processes in the pre-run-time schedule.

If the potential run-time overhead of the Main Run-Time Scheduler in the integration approach is compared with
15 the overhead of methods that schedule all the tasks at run-time, the following will be noticed:

(a) The Main Run-Time Scheduler is much simpler, and the amount of computation needed for scheduling purposes is much smaller, compared with most methods that schedule
20 all the tasks at run-time. This is because most of the important scheduling decisions have already been made before run-time. In particular, the relative ordering of P-h-k and P-s-k processes that usually form the bulk of the computation in most real-time applications, was
25 determined before run-time when the pre-run-time schedule was computed.

(b) Since at run-time, the execution order of P-h-k and P-s-k processes is the same as the relative ordering of those processes in the pre-run-time schedule, one would
30 know exactly which guaranteed periodic process may preempt which other guaranteed periodic process at run-

time. Thus one can use this information to minimize the
amount of context switching. Thus it is believed that
the run-time overhead of the Main Run-Time Scheduler
should be by far smaller than the overhead of methods
5 that schedule all the tasks at run-time.

Using the Present Invention With Multiple Processors

The methods described above can be used for scheduling processes with exclusion relations, precedence relations, and offset constraints, release time, worst-case computation time, deadline constraints, on more than one processor.

There are many possible ways that would allow one to use the methods with more than one processor. The following is just one possible set of changes to the procedures described earlier that would allow one to use the methods for scheduling processes on more than one processor. The use of the methods with multiple processors is illustrated in Example 14.

As stated earlier, instead of using a single processor method such as the method in [XuPa90] in the procedure for constructing a feasible pre-run-time schedule for a given set of periodic processes with offsets, one should use a multiple processor scheduling method, such as the method in [Xu93] in that procedure.

One simple strategy, that will be used in the embodiment described below, is to set the release time r_{p_i} of every periodic process p_i to be equal to the beginning time of its time slot in the pre-run-time schedule, i.e., $r_{p_i} = s(p_i)$. This ensures that every periodic process' actual execution will not start earlier than the beginning time of its time slot, i.e., $r_{p_i} \leq s'(p_i)$. This could prevent multiple processor anomalies that could be caused by the following situation. Some processes end earlier, and a first process that excludes a second process with a relatively short deadline is executed earlier, resulting in the first process' execution combining with the execution of a third process on another processor that also excludes the second process to increase the time interval in which the second process is blocked from execution. It is not difficult to design alternative methods that would allow each periodic process to start execution at a time earlier than the beginning of its time slot, while preventing such anomalies. Likewise, in the design of the Multiple Processor A-h-k-a Scheduler described below, there are many possible alternative strategies that would allow some more flexibility in scheduling the processes, however, this disclosure would be of too great length if every possible improvement is described.

The Multiple Processor A-h-k-a Scheduler and Multiple Processor Main-Run-Time Scheduler can be designed as follows.

Each time the Multiple Processor Run-Time Scheduler is executed, it will first
 5 try to schedule A-h-k-a processes according to the procedure below.

For any A-h-k-a process a_i and any P-g process p_l , it will be said that
 “ a_i cannot be preempted by p_l ”, if the following conditions should hold:

$$(a_i \text{ excludes } p_l) \vee (\exists a_j, a_j \in \text{A-h-k-a: } L_{a_j} < L_{p_l} \wedge a_i \text{ excludes } a_j)$$

For any pair of P-g processes p_1 and p_2 , it will be said that
 10 “the time slot of p_1 overlaps with the time slot of p_2 ”, if the following conditions should hold:

$$(s(p_1) \leq s(p_2) < e(p_1)) \vee (s(p_2) \leq s(p_1) < e(p_2))$$

The Multiple Processor A-h-k-a Scheduler Method functions as part of the Multiple
 15 Processor Main-Run-Time Scheduler to be described below.

Multiple Processor A-h-k-a-Scheduler Method:

At any time t :

20 if some A-h-k-a process a_i has arrived at time t ,
 or if some process x_i completes its computation at time t
 or if t is both the release time and start time in the pre-run-time schedule
 for some P-g process p , i.e., $t = R_p = s(p)$

then

25 for every processor k :

begin

for each A-h-k-a process a_i that has already arrived and not yet completed,
 i.e., $R'(a_i) \leq t \wedge \neg(e'(a_i) \leq t)$, check if a_i
 satisfies the following conditions,

30

Case 1: if on any processor k ,

$\exists p, p \in \text{P-g}$:

$s'(p) \geq t \wedge (a_i \text{ cannot_be_preempted_by } p) \wedge L_{a_i} \geq L_p$
 $\wedge (\nexists p_m, p_m \in \text{P-g: } t < s'(p_m) \wedge e(p_m) \leq s(p) \wedge L_{a_i} < L_{p_m} \wedge (\nexists p_1 \in \text{P-g:}$
 $p_1 \text{ excludes } a_i \wedge (p_1 \text{ 's time slot overlaps with } p_m \text{ 's time slot}))$
 $\wedge (\text{there does not exists any interval } [t, t_2] \text{ on processor } k, \text{ such that:}$

5 $t < t_2 \leq s(p)$
 $\wedge (\nexists p_l, p_l \in \text{P-g: any portion of } p_l \text{ 's time slot is mapped to any portion of the}$
 $\text{interval } [t, t_2] \text{ on the time axis corresponding to processor } k \text{ in the}$
 $\text{pre-run-time schedule})$
 $\wedge (\nexists p_j, p_m \in \text{P-g: } p_j \text{ excludes } a_i \wedge (p_j \text{ 's time slot overlaps with } [t, t_2]))$
 10 $\wedge (t_2 - t) \geq c_{a_i} +$
 $\sum_{a_k \in \text{A-h-k-a} \wedge L_{a_k} < L_p \wedge (\neg(0 \leq R'(a_k)) \vee (R'(a_k) \leq t \wedge \neg(e'(a_k) \leq t)) \vee (R'(a_k) + \min_{a_k} < s(p))) \lceil \frac{t_2 - t}{\min_{a_k}} \rceil \cdot c_{a_k}$
 then Delay a_i ;

In Case 1: a_i is delayed either if there exists the possibility that the immediate
 15 execution of a_i may cause a P-g process p with less latitude to be delayed (as shown in
 Figure 20A); or, if there exists the possibility that it may cause some A-h-k-a process
 a_j to be blocked for the duration of two processes a_i and p which both have greater
 latitude compared with a_j 's latitude (as shown in Figure 20B).

20 Case 2: if on any processor k ,
 $\exists x, x \in \text{P-g} \vee x \in \text{A-h-k-a:}$
 $s'(x) < t \wedge \neg(e'(x) \leq t) \wedge x \text{ excludes } a_i$
 then Delay a_i ;

25 In Case 2: a_i is delayed because it is not allowed to start its execution if there
 exists any process x that excludes a_i that has started but not yet completed (as shown
 in Figure 20C).

Case 3: if on processor k
 30 $\exists x, x \in \text{P-g} \vee x \in \text{A-h-k-a:}$
 $s'(x) < t \wedge \neg(e'(x) \leq t) \wedge L_x \leq L_{a_i}$
 then a_i is ineligible to execute at time t on processor k ;

In Case 3: a_i is ineligible to execute at time t on processor k because it is not allowed to preempt any process x that has less or the same latitude as a_i (as shown in Figure 20D).

5

Case 4: if on processor k ,

$\exists a_j, p, a_j \in \text{A-h-k-a}, p \in \text{P-g}:$

$s'(p) \geq t \wedge s'(a_j) < t \wedge \neg(e'(a_j) \leq t)$

$\wedge a_j \text{ excludes } p \wedge L_p \leq L_{a_i}$

10 then a_i is ineligible to execute at time t on processor k

In Case 4: a_i is is ineligible to execute at time t on processor k because it is not allowed to preempt any A-h-k-a process a_j which excludes a P-g process p with less or equal latitude compared with a_i 's latitude. (as shown in Figure 20E)

15

Case 5: on processor k ,

if $\exists x, a_j, x \in \text{A-h-k-a} \vee x \in \text{P-g},$

$a_j \in \text{A-h-k-a}:$

$s'(x) < t \wedge \neg(e'(x) \leq t)$

20 $\wedge x \text{ excludes } a_j$

$\wedge L_{a_j} < L_x \wedge L_{a_j} < L_{a_i}$

then a_i is ineligible to execute at time t on processor k .

In Case 5: a_i is ineligible to execute at time t on processor k because it is not allowed to preempt any process x that excludes some other A-h-k-a process a_j which has a latitude that is less than both x and a_i 's latitude, because that may cause a_j to be blocked by the duration of more than one process with greater latitude (as shown in Figure 20G).

30 Case 6: if on processor k

$\exists p, p \in \text{P-g}:$

$R_p \leq t \wedge \neg(e'(p) \leq t) \wedge L_p \leq L_{a_i}$

$\wedge \neg(s'(a_i) < t \wedge (a_i \text{ cannot_be_preempted_by } p))$

$\wedge \nexists p_i, p_i \in \text{P-g: } s(p_i) \leq s(p) \wedge \neg(e'(p_i) \leq t)$

$\wedge \neg(s(p_i) \leq s(p) \wedge e(p) < e(p_i))$

then a_i is ineligible to execute at time t on processor k ;

5

In Case 6: a_i is ineligible to execute at time t on processor k so that it can be preempted by a P-g process p that has a latitude that is less than or equal to a_i 's latitude, when a_i does not exclude p and does not exclude any A-h-k-a process with a latitude that is shorter than p 's latitude (as shown in Figure 20H).

10 end;

For each processor k , select, among all processes $a_i \in \text{A-h-k-a}$, such that a_i has already arrived and not yet completed, and a_i is NOT Delayed, and a_i is NOT ineligible to execute at time t on processor k , the process which has the shortest deadline and execute

15 that process on processor k . If more than one process is thus selected, select among them the process that has the smallest index.

end;

20 return to Multiple Processor Main Run-Time Scheduler;

Multiple Processor Main-Run-Time-Scheduler Method:

25

At any time t :

if some process x has arrived at time t , or has completed at time t ,

or if t is both the release time and start time in the pre-run-time schedule

for some P-g process p , i.e., $t = R_p = s(p)$

30 then execute the Multiple Processor Main-Run-Time-Scheduler as follows:

execute the Multiple Processor A-h-k-a-Scheduler;

For each processor k , if some A-h-k-a process a_i was selected for
 execution at time t on processor k by the A-h-k-a Scheduler
 then execute a_i

5 else begin
 if on processor k ,
 $\exists p, p \in \text{P-g: } s'(p) \leq t \wedge \neg(e'(p) \leq t)$
 (there exists p that has started and has not completed)
 then continue to execute p .
 10 else
 if on processor k ,
 $\exists p, p \in \text{P-g: } R_p \leq t \wedge \neg(e'(p) \leq t)$
 (there exists p that is ready and has not completed)
 then execute p
 15 else
 if $\exists a_i, a_i \in \text{A-s-k: } R_{a_i} \leq t \wedge \neg(e'(a_i) \leq t)$
 $\wedge \nexists x : (s'(x) < t \wedge \neg(e'(x) \leq t) \wedge ((x \text{ excludes } a_i)$
 $\vee (\exists a_j, a_j \in \text{A-s-k: } s'(x) < t \wedge \neg(e'(x) \leq t) \wedge x \text{ excludes } a_j$
 $\wedge L_{a_j} < L_x \wedge L_{a_j} < L_{a_i}))$
 (there exists A-s-k process a_i that is ready and has not completed,
 and there does not exist any other process x such that x excludes
 a_i or x excludes some process a_j such that a_j has a latitude that is
 less than both x 's and a_i 's latitude, and x has started but not com-
 pleted) then select among them, a process a_i that has the shortest
 20 deadline; if among such processes there are some that have already
 started, then choose a process that has already started; and execute
 a_i ;
 else
 if $\exists a_i, a_i \in \text{A-s-u: } R_{a_i} \leq t \wedge \neg(e'(a_i) \leq t)$
 $\wedge \nexists x : (s'(x) < t \wedge \neg(e'(x) \leq t) \wedge ((x \text{ excludes } a_i)$
 $\vee (\exists a_j, a_j \in \text{A-s-u: } s'(x) < t \wedge \neg(e'(x) \leq t) \wedge x \text{ excludes } a_j$
 30

$\wedge L_{a_j} < L_x \wedge L_{a_j} < L_{a_i}))$

(there exists A-s-u process a_i that is ready and has not completed,
and there does not exist any other process x such that x excludes
 a_i or x excludes some process a_j such that a_j has a latitude that
is less than both x 's and a_i 's latitude, and x has started but not
completed)

then select among them, a process a_i that has the shortest deadline;
if among such processes there are some that have already started,
then choose a process that has already started; and execute a_i ;

end;

The multiple processor simulation method for determining the worst-case response time of A-h-k-a processes can be designed as follows:

Multiple processor method for computing the worst-case response time of an A-h-k-a process a_i corresponding to a feasible pre-run-time schedule of guaranteed periodic processes consisting of an initial part of the pre-run-time schedule $S_0(t_0)$, in the interval $[0, t_0]$; and a repeating part of the pre-run-time schedule $S_{LCM}(prd_{LCM})$, in the interval $[t_0, t_0 + prd_{LCM}]$:

```

10  fail:= false;
    for  $t_s := 0$  to  $t_0 + prd_{LCM} - 1$  do
    begin
        For each A-h-k-a process  $a_b$ , such that  $a_b \in \text{A-h-k-a} \wedge L_{a_b} > L_{a_i} \wedge \exists x_k, x_k \in$ 
        A-h-k-a  $\forall x_k \in \text{P-g}$ :  $a_b$  excludes  $x_k \wedge L_{x_k} \leq L_{a_i}$ , do the following:
15    let  $a_b$  arrive at time  $t_s - 1$ , and use the Multiple Processor A-h-k-a Scheduler
        and Multiple Processor Main Run-Time Scheduler to schedule  $a_b$  and  $a_i$  to
        obtain a response time of  $a_i$ , called  $RE_1(a_i, t_s, a_b)$ , corresponding to each  $a_b$ 
        according to the assumptions (1)-(6) below, with the additional assumption
        that  $a_b$  can always start its execution at time  $t_s - 1$  (including when  $t_s = 0$ )
20    except if at time  $t_s - 1$  there exists some periodic process  $p$ , such that  $t_s < s(p)$ 
        and  $(a_b \text{ cannot be preempted by } p) \wedge L_{a_b} \geq L_p$ , and executing  $a_b$  at time  $t_s - 1$ 
        may cause  $p$  to miss its deadline, that is,  $a_b$  is delayed by the conditions in Case
        1 of the Multiple Processor A-h-k-a Scheduler. At time  $t = t_s - 1$ , assume that
        the condition " $s'(p) \geq t$ " is true for every periodic process  $p$  such that  $t_s < s(p)$ 
25    when checking whether  $a_b$  should be delayed by the conditions of Case 1 of
        the Multiple Processor A-h-k-a Scheduler. When computing  $RE_1(a_i, t_s, a_b)$ , if
         $\exists p_l, p_l \in \text{P-g} \wedge s(p_l) \leq t_s < e(p_l)$ , then assume that  $p_l$  has already completed
        at time  $t_s - 1$ , that is, this instance of  $p_l$  will not have any effect on  $a_b$ ,  $a_i$ , or
        any other process in the system.

```

30

(Let each A-h-k-a process a_b that can possibly block a_i , arrive at time $t_s - 1$ and determine which one among them will block a_i for the greatest amount of time.)

After obtaining $RE_1(a_i, t_s, a_b)$ for every such a_b , use the Multiple Processor A-h-k-a Scheduler and Multiple Processor Main Run-Time Scheduler to schedule a_i to obtain another response time of a_i , called $RE_2(a_i, t_s)$, according to the assumptions (1)-(6) below, with the additional assumption that no A-h-k-a process a_b , such that $a_b \in \text{A-h-k-a} \wedge L_{a_b} > L_{a_i} \wedge \exists x_k, x_k \in \text{A-h-k-a} \vee x_k \in \text{P-g}$: a_b excludes $x_k \wedge L_{x_k} \leq L_{a_i}$ had ever arrived. When computing $RE_2(a_i, t_s)$, if $\exists p_l, p_l \in \text{P-g} \wedge s(p_l) \leq t_s < e(p_l)$, then assume that $s'(p_l) = s(p_l) \wedge e'(p_l) = e(p_l)$; {i.e., p_l started at the beginning of its time slot and will complete its computation at the end of its time slot in the pre-run-time schedule that was computed using adjusted computation times.

(1) a_i arrives in the system at time t_s .

(2) Unless a_i is delayed because of the conditions in Case 1 of the Multiple Processor A-h-k-a Scheduler, (see (3) below), let the A-h-k-a processes a_j in the set $\{a_j | L_{a_j} \leq L_{a_i} \wedge a_j \text{ excludes } a_i\}$ arrive one by one in a serial sequence such that each process in the set arrives exactly at the same instant that the process before it in the sequence has just completed, with the first process in the sequence arriving at the time that a_b has just completed if a_b is able to block a_i , and at the earliest time t , $t_s \leq t$ that it can be executed, if a_b does not block a_i ; let every other A-h-k-a process a_j , such that $L_{a_j} \leq L_{a_i}$ arrive at the time that the last process in the above serial sequence has completed; or at the following instants in time: $R_{a_j}(k) = t_s + k * \min_{a_j}$, $k = 0, 1, 2, \dots, \lfloor \frac{d_{a_i}}{\min_{a_j}} \rfloor$, if no such processes in the above set exist, and be scheduled before a_i whenever a_i and a_j have both arrived and a_i has not yet started. If a_j is delayed by any of the conditions in Cases 1-6 of the Multiple Processor A-h-k-a Scheduler then let a_i be delayed by the same amount of time.

For each such a_j 's subsequent arrival times, use the arrival times: $R_{a_j}(k) = t_s + k * \min_{a_j}$, and whenever there is more than one such process arriving at a time that any such process is executing or has arrived but not completed, modify their arrival times as described above.

5

(All A-h-k-a processes that have shorter deadlines and that exclude a_i arrive in a serial sequence that maximizes the time that a_i is excluded, all other A-h-k-a processes whose deadlines are shorter or equal to a_i 's deadline arrive at the end of that sequence if any, and are put into execution before a_i .

10

(3) Whenever the conditions in Case 1 of the Multiple Processor A-h-k-a Scheduler become true for a_i and some P-h-k process p at some time t , i.e.: if on any processor k , $\exists p, p \in P\text{-g}$:

$$s'(p) \geq t \wedge (a_i \text{ cannot be preempted by } p) \wedge L_{a_i} \geq L_p$$

$$\wedge (\nexists p_m, p_m \in P\text{-g}: t < s'(p_m) \wedge e(p_m) \leq s(p) \wedge L_{a_i} < L_{p_m} \wedge (\nexists p_1 \in P\text{-g}:$$

15

$$p_1 \text{ excludes } a_i \wedge (p_1 \text{ 's time slot overlaps with } p_m \text{ 's time slot}))$$

$$\wedge (\text{there does not exists any idle interval } [t, t_2] \text{ on some processor } k, \text{ such that:}$$

$$t < t_2 \leq s(p)$$

$$\wedge (\nexists p_j, p_m \in P\text{-g}: p_j \text{ excludes } a_i \wedge (p_j \text{ 's time slot overlaps with } [t, t_2]))$$

$$\wedge (t_2 - t) \geq c_{a_i} +$$

20

$$\sum_{a_k \in A\text{-h-k-a} \wedge L_{a_k} < L_p \wedge (\neg(0 \leq R'(a_k)) \vee (R'(a_k) \leq t \wedge \neg(e'(a_k) \leq t)) \vee (R'(a_k) + \min_{a_k} < s(p)))$$

$$\lceil \frac{t_2 - t}{\min_{a_k}} \rceil \cdot c_{a_k}$$

let t also be the earliest time that the conditions in Case 1 become true for that instance of p and a_i ,

then for every other A-h-k-a process a_j that belongs to the following set:

25

$$\{a_j | a_j \in A\text{-h-k-a} \wedge j \neq i \wedge L_{a_j} \leq L_{a_i} \wedge$$

$$((\neg(0 \leq R'(a_j)) \vee (R'(a_j) \leq t \wedge \neg(e'(a_j) \leq t)) \vee (R'(a_j) + \min_{a_j} < s(p)))$$

$$\vee (s'(a_j) \leq t_s \wedge t - 1 \leq e'(a_j) \wedge s'(a_j) < t))\}$$

(a_j has a deadline that is shorter than or equal to a_i 's deadline and, either a_j has never arrived; or a_j has arrived but has not completed its computation; or a_j may arrive again before time $s(p)$; or at time $t - 1$ a_i was blocked by a_b and a_j started its execution before t),

30

“delay” a_j ’s arrival time to occur at the following time: let the A-h-k-a processes a_j in the set $\{a_j | L_{a_j} \leq L_{a_i} \wedge a_j \text{ excludes } a_i\}$ arrive one by one in a serial sequence such that each process in the set arrives exactly at the same instant that the process before it in the sequence has just completed, with the first process in the sequence arriving at the time that p has just completed; let every other A-h-k-a process a_j , such that $L_{a_j} \leq L_{a_i}$ arrive at the time that the last process in the above serial sequence has completed; or at the completion time of p , $e(p)'$, if no such processes in the above set exist, and be scheduled before a_i whenever a_i and a_j have both arrived and a_i has not yet started. If a_j is delayed by any of the conditions in Cases 1-6 of the Multiple Processor A-h-k-a Scheduler, then let a_i be delayed by the same amount of time. If at time $s(p)$ the conditions in Case 1 of the Multiple Processor A-h-k-a Scheduler continue to be true for some other periodic process p' , then a_i should be delayed again, and the A-h-k processes a'_j that satisfy the conditions of the formula for p' should also be delayed again in similar manner. For each such a_j , let only a single instance of a_j arrive at the above times, even if originally there could be several instances of a same process a_j that satisfy the conditions above.

For each such a_j ’s subsequent arrival times after $s(p)$, use the same arrival times that were determined in (2), i.e., a_j ’s subsequent arrival times after $s(p)$ will be: $R_{a_j}(k) = t_s + k * \min_{a_j}$ such that $R_{a_j}(k) > s(p)$, and whenever there is more than one such process arriving at a time that any such process is executing or has arrived but not completed, modify their arrival times as described above.

(If at time t there exists more than one process p for which the conditions of Case 1 are true for p and a_i , then let the above apply to the process p among them that has the latest $s(p)$ time in the pre-run-time schedule.)

(if a_i is delayed due to the conditions in Case 1, then an A-h-k-a process a_j could delay a_i by a maximum amount by arriving at the above described times.)

(4) If the end of the current instance of the repeating part of the pre-run-time schedule is reached, continue at the beginning of the next instance of the repeating part of the pre-run-time schedule.

(5) If a_i 's deadline d_{a_i} is reached but a_i has not yet completed its computation, then set $fail := true$ and exit from the procedure.

(6) If a_i 's computation is completed before its deadline d_{a_i} , then record the completion time of a_i as the response time of a_i (either $RE_1(a_i, t_s, a_b)$ for the current a_b , or $RE_2(a_i, t_s)$ when no such a_b is assumed to have arrived at time $t_s - 1$).

After the response time $RE_1(a_i, t_s, a_b)$ corresponding to every a_b that may block a_i has been computed, and the response time $RE_2(a_i, t_s)$ that assumed that no such a_b had arrived and blocked a_i has also been computed, set the response time of a_i with arrival time t_s , $RE(a_i, t_s)$ to be equal to the greatest among them, i.e., $RE(a_i, t_s) = \max\{RE_1(a_i, t_s, a_b), RE_2(a_i, t_s)\}$, and exit from the current iteration of the loop for this value of t_s , and start the next iteration for $t_s := t_s + 1$.

end;

if not fail then

$RE_{a_i} := \max\{RE(a_i, t_s) \mid t_s = 0, 1, \dots, LCM - 1\}$;

Assuming that the same `adjusted_capacity` function is used for adjusting the computation times of periodic processes, the Multiple Processor A-h-k-a Scheduler also has the following properties, similar to the properties of the version of the A-h-k-a Scheduler described earlier :

5

Property 1. Each P-g process p 's execution can only be delayed by A-h-k-a processes that have less latitude than p 's latitude. A P-g process will never be delayed by any A-h-k-a process that has a greater or equal latitude.

10

Property 2. Any A-h-k-a process a_i cannot be blocked by more than one critical section belonging to A-h-k-a processes that have deadlines greater than a_i 's deadline.

Property 3. No deadlocks can ever occur.

15

Property 4. Each P-g process p will always be completed on or before $e(p)$, that is, the end of the time slot allocated to p in the pre-run-time schedule.

Example 14

20

Suppose that a multiprocessor system consists of two processors, two asynchronous processes with hard deadlines and known characteristics (A-h-k processes): a_A and a_E ; and 3 periodic processes with hard deadlines and known characteristics (P-h-k processes) p_B , p_C , and p_D as follows.

a_A : $c_{a_A} = 2, d_{a_A} = 8, \min_{a_A} = 8$;

25

a_E : $c_{a_E} = 2, d_{a_E} = 14, \min_{a_E} = 1,000$;

p_B : $r_{p_B} = 1, c_{p_B} = 3, d_{p_B} = 4, \text{prd}_{p_B} = 6, 0 \leq o_{p_B} \leq 3$;

p_C : $r_{p_C} = 0, c_{p_C} = 1, d_{p_C} = 2, \text{prd}_{p_C} = 4; o_{p_C} = 0$;

p_D : $r_{p_D} = 0, c_{p_D} = 1, d_{p_D} = 1, \text{prd}_{p_D} = 3, 0 \leq o_{p_D} \leq 4$;

It is assumed that the application requires that $o_{p_C} = 0, 0 \leq o_{p_B} \leq 3$, and
 30 $0 \leq o_{p_D} \leq 4$, and asynchronous process a_A may make its first request at time 0. It is also assumed that the application requires the following relations be satisfied: a_A excludes p_D , p_D excludes a_A , a_A excludes p_B , p_B excludes a_A , p_C excludes p_D , p_D excludes p_C ,

a_E excludes p_B , p_B excludes a_E ;

Suppose that when converting a_A to a periodic process, when determining d_{newp_A} :

$$d_{newp_A} = c_{a_A} + \text{conversion_room}(a_A);$$

5

the following formula was used in the `conversion_room` function:

$$\text{conversion_room}(a_A) =$$

10

$$\left\lceil \frac{\sum_{p_j \in (S_P \cup S_D) \wedge d_{p_j} \leq d_{x_i} \lceil \frac{d_{x_i}}{prd_{p_j}} \rceil * c_{p_j}}{m} \right\rceil + \sum_{a_j \in S_a \wedge d_{a_j} \leq d_{x_i} \wedge i \neq j} \left\lceil \frac{d_{x_i}}{min_{a_j}} \right\rceil * c_{a_j}$$

where m is the number of processors.

15

Then in the procedure for converting A-h-k processes into periodic processes, prior to entering the while loop, $d_{newp_A} = c_A + (c_B + c_C + c_D)/m = 2 + [(2 + 1 + 1)/2] = 4$. After the second iteration of the while loop, $d_{newp_A} = c_A + [(c_C + c_D)/m] = 2 + [(1 + 1)/2] = 3$. $prd_{newp_A} = (d_A - d_{newp_A} + 1) = 8 - 3 + 1 = 6$; $0 \leq o_{newp_A} \leq prd_{newp_A} - 1 = 6 - 1 = 5$.

20

Suppose further that the system designer wanted to increase the chances of a_A being converted into a periodic process, so the `threshold(a_A)` was assigned a low value of 0.5.

$$RPC_{newp_A} = c_{newp_A}/prd_{newp_A} = 2/6 = 0.33.$$

$$RPC_{a_j} = c_{a_A}/min_{a_j} = 2/8 = 0.25.$$

As $\text{threshold}(a_A) * RPC_{newp_A} = 0.5 * 0.33 \leq RPC_{a_A} = 0.25$, the procedure will convert a_A into a periodic process $newp_A$.

25

Suppose also that the system designer did not want a_E to be converted into a periodic process, so `threshold(a_E)` was assigned a high value of 50. The procedure will not convert a_E into a periodic process.

30

If the method in [Xu93] was used by the procedure for constructing a feasible pre-run-time schedule for a given pre-run-time schedule with offsets, it will find the feasible schedule for $newp_A$, p_B , p_C , and p_D , on two processors illustrated in Fig. 20, when the offsets are set to the following values: $o_{newp_A} = 2$, $o_{p_B} = 3$, and $o_{p_D} = 1$. The feasible schedule consists of a non-repeating initial schedule $S_0(1)$ for the interval

[0,1], and a repeating schedule $S_{LCM}(12)$ that is of length equal to the Least Common Multiple of the periods of $newp_A$, p_B , p_C , and p_D , which is $LCM(6, 6, 4, 3) = 12$.

If a_E is scheduled by the Multiple Processor A-h-k-a Scheduler using the information in the pre-run-time schedule including the processes $newp_A$, p_B , p_C , p_D constructed by the Pre-run-time Scheduler above, then a_E 's worst-case response time will happen when a_E makes a request at time 3, and will be delayed by the conditions in Case 1 of the Multiple Processor A-h-k-a Scheduler at time 3. a_E will be executed from time 13 to time 15 after p_{B_1} has completed. The multiple processor simulation procedure for determining each A-h-k-a process' worst-case response time will simulate this execution in which a_E 's worst-case response time is $RE(a_E, t_s) = RE(a_E, 3) = e'(a_E) - s'(a_E) = 15 - 3 = 12 \leq d_{a_E} = 14$. In this case a_E is guaranteed to always meet its deadline. See Fig. 21.

Suppose the value chosen for $threshold(a_A)$ is greater than 0.75, then A-h-k process a_A will not be converted into a new periodic process. If a_A is scheduled by the Multiple Processor A-h-k-a Scheduler using the information in the pre-run-time schedule including the processes, p_B , p_C , p_D constructed by the Pre-run-time Scheduler above, then a_A 's worst-case response time will happen when a_A makes a request at time 3, and will be delayed by the conditions in Case 1 of the Multiple Processor A-h-k-a Scheduler at time 3. a_A will be executed from time 8 to time 10 after p_{D_2} has completed. a_E 's response time is $RE(a_A, t_s) = RE(a_A, 3) = e'(a_A) - s'(a_A) = 10 - 3 = 7 \leq d_{a_A} = 14$. In this case a_A is guaranteed to always meet its deadline. See Fig. 22.

However, while it is possible to guarantee that both a_A and a_E will always meet their respective deadlines when a_A is converted into a new periodic process $newp_A$ as illustrated in Fig. 21; it is interesting to note that, if a_A is not converted into a new periodic process and remains asynchronous, then it would be impossible to guarantee that a_E will always meet its deadline, because there exist certain times, e.g., any time between 13 and 16, at which, if a_E is put into execution, it may be preempted by a_A and cause p_B to miss its deadline. Prohibiting a_A from preempting a_E by adding the exclusion relation a_E *excludes* a_A is not a solution, because not allowing a_A to preempt a_E will increase a_A 's worst-case response time to exceed a_A 's deadline. This example illustrates

that, in certain cases, it may be advantageous to convert an asynchronous process with a hard deadline and known characteristics into a new periodic process and schedule it before run-time.

5 It should be noted that various other embodiments of the present invention may be designed.

For example, tables of safe start time intervals for asynchronous processes may be used. In the methods described prior to the above description of scheduling processes on multiple processors, each periodic process was not restricted to execute within the time slot that was used to reserve processor capacity for that periodic process in the pre-run-time schedule. However, it is possible to enforce the requirement that every periodic process must execute strictly within its reserved time slot in the pre-run-time schedule, simply by changing each periodic process p 's release time R_p to be equal to the beginning of its time slot in the pre-run-time schedule, i.e., set $R_p = s(p)$ for every p .

20 One advantage of doing this, is that it will make the execution times of periodic processes highly predictable, and thus allow construction of tables of "safe start time intervals" for asynchronous processes before run-time. Such tables would allow asynchronous processes to be scheduled at run-time by simple table lookup, and substantially reduce the run-time overhead of scheduling asynchronous processes.

The safe start time intervals can be computed by using the A-h-k-a Scheduler (or Multiple Processor A-h-k-a Scheduler) to determine, for each point in time t of the pre-run-time schedule, and for each processor k ,

whether each asynchronous process a_i can be put into execution at time t on processor k .

Example 15

5

For the asynchronous process a_E , a_A in the system in Example 14, the following "safe start time tables" may be constructed.

When a_A is converted into a new periodic process
10 newp_A, and the pre-run-time schedule is as shown in Figure 21, the safe start time table for a_E should preferably contain the following "safe start time intervals":
on processor 1: empty;
15 on processor 2: $\{(k * 12) + 1, (k * 12) + 2\}$, $k = 0, 1, 2, \dots$

When a_A is not converted into a new periodic process, and the pre-run-time schedule is as shown in
20 Figure 22, the safe start time table for a_A should preferably contain the following "safe start time intervals":
on processor 1: $\{(k * 6) + 2\}$, $k = 0, 1, 2, \dots$
on processor 2: $\{(k * 12) + 2\}$, $k = 0, 1, 2, \dots$

25

When a_A is not converted into a new periodic process, and the pre-run-time schedule is as shown in Figure 22, the safe start time table for a_E should preferably contain the following "safe start time
30 intervals":
on processor 1: empty

on processor 2: empty

The safe start time intervals define the only times at which an asynchronous process can start its
5 execution on a processor when the processor is idle without the possibility of causing some hard deadline process to miss its deadline.

Many priority and or criticality levels may be handled. One can easily adapt the present invention to
10 handle any number of priority/criticality levels.

If some set of periodic processes is to be treated at the same priority as some set of asynchronous processes, then they could be scheduled in a way similar to the way P-h-k processes and A-h-k processes are
15 scheduled as described earlier.

If some set of periodic processes is to be treated at a higher priority than some set of asynchronous processes, then they could be scheduled in a way similar to the way P-h-k processes and A-s-k
20 processes are scheduled as described earlier.

If some set of periodic processes is to be treated at a lower priority than some set of asynchronous processes, then they could be scheduled in a way similar to the way P-s-k processes and A-h-k
25 processes have been scheduled as described earlier.

If some set of periodic processes is to be treated at a lower priority than some other set of periodic processes, then they could be scheduled in a way similar to the way I scheduled P-s-k processes and
30 P-h-k processes have been scheduled as described earlier.

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If some set of asynchronous processes is to be treated at lower priority than some other set of asynchronous processes, then they could be scheduled in a way similar to the way A-s-k processes and A-h-k processes have been scheduled as described earlier.

For example, although in this specification A-s-k processes are described as having been scheduled at a priority level that is lower than P-s-k processes, a different set of asynchronous processes with soft deadlines and known characteristics, say A-s-k-2, could have been chosen, that is scheduled at the same priority level as the P-s-k processes. Then the relationship between the A-s-k-2 processes and the P-s-k processes could be handled in a way that is similar to the way the relationship between the A-h-k and P-h-k processes was handled.

When using the integration method to schedule processes with different priority levels, the following general rules should be observed:

(a) Periodic processes with known characteristics should be scheduled before run-time. The worst-case response times of asynchronous processes with known characteristics should also be determined before run-time. At run-time, the asynchronous processes should be scheduled in a way that guarantees that the timing constraints of all processes scheduled in the pre-run-time phase are always satisfied. Processes with unknown characteristics should be scheduled at a priority level that is lower than that of all processes with known characteristics.

(b) One should schedule the set of processes that have higher priority first and make sure that all their timing constraints are satisfied, before using the remaining processor capacity to schedule a set of
5 processes that have lower priority.

In the present invention, different methods for scheduling each type of process, while observing the general rules above, may be used.

The present invention can also be used in an on-
10 line mode. In such cases, in Step 2, when constructing a feasible pre-run-time schedule, when using the method described in the aforementioned 1990 article by Xu and Parnas, instead of constructing a search tree, the method can be used in a way such that it always only
15 constructs one schedule for each set of processes, which should be as fast as any existing method, and still provide better chances of finding a feasible pre-run-time schedule than other methods.

20 As noted earlier, a simplified procedure for Step 4, pre-run-time scheduling of periodic processes with soft deadlines and known characteristics, will now be described.

In order to try to find a feasible schedule of
25 all soft-deadline periodic processes together with all the guaranteed hard-deadline periodic processes using the optimal method, if a feasible schedule does not exist, then find an optimal schedule.

30

```

discontinue:= false;
nocandidate:= false;
while not discontinue do
begin{try to construct a feasible schedule}
  if  $e'(p_l) - D_{p_l} = \max\{e'(p_i) - D_{p_i} \mid p_i \in P\text{-h-k} \vee p_i \in P\text{-s-k}\}$  and  $e'(p_l) > D_{p_l}$ 
    { $p_l$  is the latest process and  $p_l$  is late}
  then
  begin{try to reduce the lateness of latest process  $p_l$ }
    candidatefound:= false;
    CandidateSet:= P-s-k
    while not candidatefound and not nocandidate do
    begin{search for candidate to revise deadline}
      select  $p_j$  such that
         $p_j \in \text{CandidateSet} \wedge d_{p_j} < d_{upplimit}(p_j) \wedge$ 
         $\text{criticality}(p_j) = \min\{\text{criticality}(p_i) \mid p_i \text{ in critical set } Z(p_l)\}$ 
        { $Z(p_l)$  is a set of processes that includes the latest
        process  $p_l$  and there is no time during which the processor
        is idle between their execution. (see [24])}
      if no such  $p_j$  exists then
        nocandidate:= true;
      else
        begin
          if  $e'(p_l) + 1 \leq d_{upplimit}(p_j)$ 
          then
            begin
              if  $j \neq l$ 
              then  $d_{p_j} := e'(p_l) + 1$ 
                {this will cause  $p_j$  to
                be scheduled after  $p_l$ 
                which may help reduce lateness}
              else  $d_{p_j} := e'(p_l)$ ;
                {if  $p_j$  itself is latest
                then set  $d_{p_j}$  such
                that  $p_j$  will not be late}
              candidatefound:= true
            end
          else remove  $p_j$  from CandidateSet
        end
    end
  end
end

```


A method and a simulation procedure for determining the response times of the A-s-k processes, for example a_i follows:

For all $a_i \in A\text{-s-k}$:

$$RE_{a_i} = c_{a_i} + \text{DelayA}(a_i, RE_{a_i}) + \text{DelayP}(a_i, RE_{a_i}) + B(a_i)$$

where

$$\text{DelayA}(a_i, RE_{a_i}) = \sum_{a_j \in A\text{-h-k} \vee (a_j \in A\text{-s-k} \wedge L_{a_j} \leq L_{a_i} \wedge j \neq i} \left\lceil \frac{RE_{a_i}}{\min_{a_j}} \right\rceil \cdot c_{a_j}$$

and

$$\text{DelayP}(a_i, RE_{a_i}) = \sum_{p_j \in P\text{-h-k} \vee p_j \in P\text{-s-k}} \left\lceil \frac{RE_{a_i}}{\text{prd}_{p_j}} \right\rceil \cdot c_{p_j}$$

and

$$B(a_i) = \max\{c_{a_j} \mid (a_j \in A\text{-s-k} \wedge L_{a_j} > L_{a_i} \wedge \exists x_k, x_k \in A\text{-s-k}: a_j \text{ excludes } x_k \wedge L_{x_k} \leq L_{a_i})\}$$

Note: In the above formula, the value of c_{p_j} is the original computation time of p_j (it does not include the time reserved for A-h-k-a processes with shorter deadlines).

The following procedure can be used to compute the worst-case response time of each A-s-k process:

```

i:= 0;
failure= false;
while i ≤ number-of-A-s-k-processes and not(failure) do
begin
  if  $a_i \in A\text{-s-k}$ 
  then
  begin
     $RE_{new_i} := c_{a_i}$ ;
    responsetimefound:= false;
    while not(responsetimefound) and not(failure) do
    begin
       $RE_{previous_i} := RE_{new_i}$ ;
       $RE_{new_i} = \text{DelayA}(a_i, RE_{previous_i}) + \text{DelayP}(a_i, RE_{previous_i}) + B(a_i)$ ;
      if  $RE_{previous_i} = RE_{new_i}$ 
      then
      begin
         $RE_{a_i} := RE_{new_i}$ ;
        responsetimefound:= true;
      end
      if ( $RE_{new_i} > \text{responsetimelimit}$ )
      then failure:= true
    end;
  end;
  i:= i + 1;
end;

```

See Example 9 for concerning use of the above procedure.

In the following description, the second method is described, which uses simulation to determine the worst-case response time of an A-s-k process. This method uses the functions of the A-h-k-a Scheduler and the Main Run-Time Scheduler, which are described earlier.

A preferred method for computing the response time of an A-s-k process a_i corresponding to a feasible pre-run-time schedule of guaranteed periodic processes comprising an initial part of the pre-run-time schedule $S_0(t_0)$, in the interval $\{0, t_0\}$; and a repeating part of the pre-run-time schedule $S_{LCM}(prd_{LCM})$, in the interval $\{t_0, t_0 + prd_{LCM}\}$ is as follows:

fail:= false;

for $t_s := 0$ to $t_0 + prd_{LCM} - 1$ do

begin

Use the Main Run-Time Scheduler to schedule a_i under the following assumptions:

(1) a_i arrives in the system at time t_s .

(2) Let every A-h-k-a process a_j arrive

at the following instants in time: $R_{a_j}(k) = t_s + k * \min_{a_j}$,

$k = 0, 1, 2, \dots, \lfloor \frac{d_{a_i}}{\min_{a_j}} \rfloor$, and be scheduled before a_i .

{ all A-h-k-a processes arrive at the same time as a_i at time t_s , and are put into execution before a_i . }

(3) Let every A-s-k process a_j , such that $L_{a_j} \leq L_{a_i}$ arrive

at the following instants in time: $R_{a_j}(k) = t_s + k * \min_{a_j}$,

$k = 0, 1, 2, \dots, \lfloor \frac{d_{a_i}}{\min_{a_j}} \rfloor$, and be scheduled before a_i whenever

a_i and a_j have both arrived and a_i has not yet started.

{ all A-s-k processes whose latitudes are less than or equal to a_i 's latitude arrive at the same time as a_i at time t_s , and are put into execution before a_i . }

(4) Let A-s-k process a_{j_1} , such that $c_{a_{j_1}} = \max\{c_{a_j} | (a_j \in \text{A-s-k} \wedge L_{a_j} > L_{a_i} \wedge \exists x_k, x_k \in \text{A-s-k} \forall x_k \in \text{P-g: } a_j \text{ excludes } x_k \wedge L_{x_k} \leq L_{a_i})\}$ arrive at the following instants in time: $R_{a_{j_1}}(k) = t_s - 1 + k * \min_{a_{j_1}}$, $k = 0, 1, 2, \dots, \lfloor \frac{d_{a_i}}{\min_{a_{j_1}}} \rfloor$
 $\{a_{j_1}$ arrives 1 time unit before a_i at time $t_s - 1$, and,
if it can be put into execution at that time, it will block a_i .}

(5) If $\exists p_l, p_l \in \text{P-g} \wedge s(p_l) \leq t_s < e(p_l)$, then assume that $s'(p_l) = s(p_l) \wedge e'(p_l) = e(p_l)$; {i.e., p_l started at the beginning of its time slot and will complete its computation at the end of its time slot in the pre-run-time schedule that was computed using adjusted computation times.}

(6) If the end of the current instance of the repeating part of the pre-run-time schedule is reached, continue at the beginning of the next instance of the repeating part of the pre-run-time schedule.

5 (7) If a_i 's computation is completed before its response time limit, then record the completion time of a_i as its response time $RE(a_i, t_s)$, and exit from the current iteration of the loop for this value of t_s , and start the next iteration for $t_s := t_s + 1$.

10 (8) If a_i 's response time limit is reached but a_i has not yet completed its computation, then set $fail := true$ and exit from the procedure.

end;

if not fail then

15 $RE_{ai} := \max\{RE(a_i, t_s) \mid t_s = 0, 1, \dots, LCM - 1\};$

It should be noted that while the above-described methods can be carried out in a software programmed processor, and have been described with such a processor as an example, they, or one or more steps in
20 the methods, can alternatively be carried out by hardware such as gate arrays or by other fixed or programmable structures, or combinations of these structures.

25 A processor can be any physical or virtual structure which can perform one or more functions. A processor can be a machine, a computer processor, a logic device, an organization, etc. A process can be any task or job that requires a finite amount of time to
30 complete on a certain processor. Computation time is

the amount of time that a process requires from start to completion on a certain processor.

Figure 24 illustrates an example of a system on which the methods described herein can be carried out.

5 Any of plural peripherals 1 provide input signals which require processing. For example, peripherals can be a keyboard, a signal from an emergency response telephone system, an alarm clock, a program running in background on a processor, a pipeline, etc. A memory 3 stores
10 processes, e.g. series of instructions, for carrying out the various processes. The memory can be in the form of any storage structure, and can be, for instance a store for a series of electronic, pneumatic, hydraulic, etc. control signals for operating a plurality of industrial
15 processes that require scheduling in accordance with the demands of the input signals. In one embodiment, the memory can be a hard random access memory and/or a disk drive of a computer, of well known form and the input signals can be electronic. In another embodiment, in
20 the case in which the memory is in the form of industrial process structures, the input signals can be fluids, photons, objects, audio, data or other signals, etc, which are to be scheduled to be processed by the various industrial processes.

25 The input signals and the memory are coupled to a processor 4 of any form with which the present invention can be operated, such a computer processor. The processor can be a single processor, or plural processor which can operate in accordance with Example
30 14. The processor or processors have an output which is coupled to an output device or system 5, which receives

the output result of the operation of the processes by the processor.

The memory preferably also has a portion 7 for storing a pre-run-time schedule, and a portion 9 for
5 storing a run-time schedule for execution of the processes stored in the memory 3.

In operation, the processor receives input signals which demand that processes stored in the memory 3 (or which are received from other control or interrupt
10 inputs, not shown) are executed. As described earlier in this specification, some of these processes can be periodic and some can be asynchronous. The processor, operating using an operating system stored in the memory 3, obtains the characteristics of the various processes
15 from the memory, and creates or simulates a pre-run-time schedule, then creates or simulates a run-time schedule which uses the pre-run-time schedule, as described earlier in this specification. It then executes the run-time schedule as described herein, providing an
20 output to the output device or system.

Figure 24A provides another example of a multiprocessor system on which the methods described herein can be carried out. The real-time system consists of a controlling system having two parts, a
25 pre-run-time scheduling subsystem 10 and a run-time scheduling subsystem 11, and a controlled system 12. The controlled system 12 has data/control buses linking the various components. The controlled system 12 is comprised of a set of periodic processes p1, p2, .. pn,
30 a set of asynchronous processes a1, a2, ... aj, and one or more processors 13a, 13b, ... 13m. Each processor 13a - 13m may have local memory and shared memory. On each processor 13a - 13m the processes, either periodic

or asynchronous, may be executed. Each process can be a task that requires a finite amount of time to complete on a processor that may have memory resources. Examples of such processes include : a service routines that
5 periodically monitors conditions on a physical system and sends a signal when the conditions meet a certain standard or a task that responds to random user initiated requests. Any of the processes can be a complete subsystem unto itself comprising a processor
10 and a memory that requires the use of some services offered by controlled system 12 in order to execute other periodic or asynchronous processes.

The pre-run-time scheduling subsystem 10 consists of one or more processors 14 that are used to
15 perform pre-run-time scheduling. The pre-run-time scheduling subsystem scheduler (not shown) acquires information about the periodic processes such as constraints, release time, deadline, offset, precedence, and exclusion relations. The scheduler then uses this
20 information to determine whether each asynchronous process should be converted into a new periodic process or not. After converting any suitable subset of asynchronous processes into new periodic processes but before run-time of the processes, the pre-run-time
25 scheduler constructs a pre-run-time schedule for all the periodic processes which satisfies all the constraints and relations defined on the periodic processes. The scheduler then makes this schedule available to the run-time scheduling subsystem 11.

30 The run-time scheduling subsystem 11 consists of one or more processors 15 that are used to perform run-time scheduling of the periodic and asynchronous processes. The run-time scheduling subsystem 11 uses

the information 16 provided by the pre-run-time scheduler and stored in memory, to schedule the processes for execution on processor(s) 15. The processors 13a - 13m in the controlled system 12 on which the periodic or asynchronous processes are executed may share memory and other resources. Consequently, it is important to to enforce exclusion relations on the execution of the processes to prevent more than one process from accessing a shared memory resource at the same time. The pre-run-time scheduling subsystem 10 and the run-time scheduling subsystem 11 work together to control the execution of all the processes in the controlled system 12. These two subsystems 10 and 11 guarantee that all the processes in the controlled system 12 are completed before their respective deadlines and that all the constraints and relations among the processes are satisfied.

While Figure 24A shows the run-time scheduling
20 subsystem 11 as being within the controlled system 12,
this is not necessary for the proper working of the
invention. The run-time scheduling subsystem 11 can be
separate from the controlled system 12.

Some applications of the present invention can
25 be in aircraft flight control, plant process control,
traffic control, communication systems, multimedia,
signal control of the internet, electronic commerce,
electronic buses, computer operation, etc.

A person understanding the above-described
30 invention may now conceive of alternative designs, using
the principles described herein. All such designs which
fall within the scope of the claims appended hereto are
considered to be part of the present invention.

I claim:

1. A method of scheduling on one or more processors, executions of both periodic and asynchronous
5 real-time processes having hard or soft deadlines, comprising automatically generating a pre-run-time schedule comprising mapping from a specified set of periodic process executions to a sequence of time slots on one or more processor time axes, each of the time
10 slots having a beginning time and an end time, reserving each one of the time slots for execution of one of the periodic processes, a difference between the end time and the beginning time of each of the time slots being sufficiently long that execution of all of the periodic
15 processes, including satisfaction of predetermined constraints and relations comprising at least one of release time, worst-case computation time, period, deadline, deadline nature, offset and permitted range of offset constraints, and precedence and exclusion
20 relations and criticality levels can be completed between the beginning time and end time of respective time slots, and executing the processes in accordance with the schedule during run-time of the processor.

25 2. A method as defined in claim 1, including the step of converting at least one asynchronous process to a corresponding new periodic process prior to the mapping step, and mapping the new periodic process in a manner similar to mapping of other periodic processes.

30

3. A method as defined in claim 1, including the step of converting all asynchronous processes that can be contained without conflict in the time slots with periodic processes including new periodic processes
35 converted from asynchronous processes, into new periodic

processes prior to the mapping step, and mapping all new periodic processes in a manner similar to mapping of other periodic processes.

5 4. A method as defined in claim 3, including further executing all non-converted asynchronous processes during run-time of the processor at times which do not interfere with execution of processes contained in the pre-run-time schedule.

10

 5. A method as defined in claim 1 including, following pre-run-time scheduling and during run-time of the processor, the step of scheduling executions of a specified set of periodic and asynchronous processes
15 such that all known ones of said specified constraints and relations will always be satisfied, the specified constraints and relations further comprising, for asynchronous processes, at least one of worst-case computation time, deadline, deadline nature and minimum
20 time between two consecutive requests, and beginning time and end time of every time slot reserved for every periodic process execution in the pre-run-time schedule.

 6. A method as defined in claim 3 including,
25 following pre-run-time scheduling and during run-time of the processor, the step of scheduling executions of a specified set of periodic and asynchronous processes such that all known ones of said specified constraints and relations will always be satisfied, the specified
30 constraints and relations further comprising, for asynchronous processes, at least one of worst-case computation time, deadline, deadline nature and minimum time between two consecutive requests, and beginning time and end time of every time slot reserved for every
35 periodic process execution in the pre-run-time schedule.

7. A method as defined in claim 1, including scheduling, within the pre-run-time schedule, said difference between the end time and the beginning time
5 of each of said periodic time slots with sufficient time capacity for execution of all asynchronous processes that have less latitude than considered ones of periodic processes in meeting their respective deadlines.

10 8. A method as defined in claim 3, including scheduling, within the pre-run-time schedule, said difference between the end time and the beginning time of each of said periodic time slots with sufficient time capacity for execution of all unconverted asynchronous
15 processes that have less latitude than latitude than considered ones of periodic processes in meeting their respective deadlines.

9. A method for automatically adjusting lengths
20 of periods of a predetermined set of periodic processes, comprising storing and sorting a list of reference periods, setting the length of the period of each periodic process to the length of the largest reference period that is no larger than an original period of the
25 periodic process to form adjusted periods, and storing the adjusted periods for subsequent use in scheduling executions of the periodic processes.

10. A method as defined in claim 1, including
30 prior to the mapping step, automatically adjusting lengths of periods of a predetermined set of periodic processes, by storing and sorting a list of reference periods, setting the length of the period of each periodic process to the length of the largest reference
35 period that is no larger than an original period of the

periodic process to form adjusted periods, and storing the adjusted periods for subsequent use in pre-run-time scheduling of executions of the periodic processes.

5 11. A method as defined in claim 8, including prior to the mapping step, automatically adjusting lengths of periods of a predetermined set of periodic processes by storing and sorting a list of reference periods, setting the length of the period of each
10 periodic process to the length of the largest reference period that is no larger than an original period of the periodic process to form adjusted periods, and storing the adjusted periods for subsequent use in pre-run-time scheduling of executions of the periodic processes.

15 12. A method as defined in claim 9, including setting the length of each reference period to be equal to the product of n powers, the base of each of the n powers being a distinct prime number, the n bases of the
20 n powers being the first and smallest n prime numbers, the exponent of each of the n powers being bounded by an exponent upperbound, the sorted list of reference periods including every product of every said n powers.

25 13. A method as defined in claim 12, including controlling tradeoff between differences between original period lengths and the adjusted period lengths, and the length of a least common multiple of the adjusted period lengths, by values of the n exponent
30 upperbounds and the value of n .

 14. A method as defined in claim 1 including, prior to generating the pre-run-time schedule, determining whether each hard deadline asynchronous
35 process should or should not be converted into a new

periodic process, and then converting a subset of a
predetermined set of asynchronous processes having a
worst-case computation time, minimum time between two
requests characteristics and hard deadline constraints,
5 which have been determined to be convertible, into a set
of new periodic processes having release time, worst-
case computation time, period, hard deadline, and
permitted range of offset constraints, and reducing
possible timing conflicts with other hard deadline
10 periodic or hard deadline asynchronous processes with
less latitude in meeting their deadlines, by taking into
consideration the computation time requirements of the
latter processes when determining the deadline of the
new periodic process.

15

15. A method as defined in claim 1 including,
prior to generating the pre-run-time schedule,
determining whether each hard deadline asynchronous
process should or should not be converted into a new
20 periodic process, and then converting a subset of a
predetermined set of asynchronous processes having a
worst-case computation time, minimum time between two
requests characteristics and hard deadline constraints
which have been determined to be convertible, into a set
25 of new periodic processes having release time, worst-
case computation time, period, hard deadline, and
permitted range of offset constraints, wherein a
permitted range of offset of the new periodic process
being is a subinterval of an interval or a full interval
30 that begins at a predetermined start time, and ends at a
time equal to the sum of the earliest time that an
asynchronous process can make a request for execution
plus the period length of the new periodic process minus
one time unit.

35

16. A method as defined in claim 14, in which the determining step is performed by calculating whether a ratio of processing capacity of the processor which is required to be reserved for new periodic processes, to processor capacity that is required for the asynchronous process if left unconverted, exceeds a predetermined threshold value.

17. A method as defined in claim 1, including generating the pre-run-time schedule as a feasible two-part pre-run-time-schedule for execution of periodic processes that may have non-zero offsets (a) an initial part which may be of zero length, and (b) a repeating part having length which is equal to a least common multiple of lengths of all the periods of the periodic processes,

all executions of all periodic processes within a time interval of length equal to the length of the least common multiple of the periodic process periods being included in the repeating part of the pre-run-time schedule, wherein all said specified constraints and relations being satisfied for all executions of all periodic processes within both said initial part and said repeating part, and

using any offset value in a permitted range of offsets of each periodic process, including any offset value in the permitted range of offsets of any new periodic process that may have been converted from an asynchronous process, to generate said feasible pre-run-time schedule.

18. A method as defined in claim 1, including generating the pre-run-time schedule as a feasible two-part pre-run-time schedule on one or more processors for execution of periodic processes that may have non-zero

using any offset value in a permitted range of offsets of each periodic process, including any offset value in the permitted range of offsets of any new periodic process that may have been converted from an asynchronous process, to generate said feasible pre-run-time schedule.

20. A method as defined in claim 17, including generating said pre-run-time schedule on a plurality of processors.

21. A method as defined in claim 14, including generating the pre-run-time schedule as a feasible two-part pre-run-time-schedule for execution of periodic processes that may have non-zero offsets (a) an initial part which may be of zero length, and (b) a repeating part having length which is equal to a least common multiple of lengths of all the periods of the periodic processes,

all executions of all periodic processes within a time interval of length equal to the length of the least common multiple of the periodic process periods being included in the repeating part of the pre-run-time schedule, wherein all said specified constraints and relations being satisfied for all executions of all periodic processes within both said initial part and said repeating part, and

using any offset value in a permitted range of offsets of each periodic process, including any offset value in the permitted range of offsets of any new periodic process that was converted from an asynchronous process, to generate said feasible pre-run-time schedule.

22. A method as defined in claim 21, including

generating said feasible pre-run-time schedule on one or more processors.

23. A method as defined in claim 21, further
5 including the steps of generating the pre-run-schedule by constructing a schedule for all executions of the periodic processes within an interval starting from zero and having length equal to maximum offset value plus a bounded number of times of the length of a least common
10 multiple of the periodic process periods, conditions for determining feasibility requiring the existence of a point in the pre-run-time schedule wherein starting from the latter point the schedule repeats in subschedule interval lengths equal to a least common multiple of
15 lengths of all the periodic process periods, timing of all executions of all periodic processes within a time interval having length equal to the length of the least common multiple of the periodic process periods being included in each said repeating subschedule interval,
20 and including satisfaction of all predetermined constraints and relations for all executions of all periodic processes within the subschedule interval starting from time zero and ending at said point plus the length of the least common multiple of the periodic
25 process periods in the schedule.

24. A method as defined in claim 23, including generating said pre-run-time schedule on a plurality of processors.

30

25. A method as defined in claim 1, including generating the pre-run-time schedule on one or more processors as a feasible two-part pre-run-time-schedule for execution of periodic processes that may have non-
35 zero offsets (a) an initial part which may be of zero

27. A method as defined in claim 1, further comprising, during run-time:

(a) detecting, at any predetermined time, whether there exists a possibility that immediate execution of a particular hard deadline asynchronous process may cause the execution of any periodic process with less latitude in meeting a deadline of the latter periodic process as compared with latitude of meeting the deadline of the particular hard deadline asynchronous process which is to be delayed beyond a predetermined time limit, even if the periodic process is not ready for execution at said any predetermined time, and

(b) delaying execution of the hard deadline asynchronous process if said possibility is found to exist, even if said possibility is the only reason for delaying the execution of said asynchronous process at said any time, and even if the delay will cause the processor to be in an idle state for a time interval of non-zero length beginning from said any time.

20

28. A method as defined in claim 1, further comprising, during run-time:

(a) detecting, at any predetermined time, whether there exists a possibility that immediate execution of a particular hard deadline asynchronous process may cause the execution of any periodic process with less latitude in meeting a deadline of the latter periodic process as compared with latitude of meeting the deadline of the particular hard deadline asynchronous process which is to be delayed beyond the end of the time slot of the periodic process in the pre-run-time schedule, even if the periodic process is not ready for execution at said any predetermined time, and

(b) delaying execution of the hard deadline
35 asynchronous process if said possibility is found to

exist, even if said possibility is the only reason for
delaying the execution of said asynchronous process at
said any time, and even if the delay will cause the
processor to be in an idle state for a time interval of
5 non-zero length beginning from said any time.

29. A method as defined in claim 1, further
comprising, during run-time:

(a) detecting, at any predetermined time, whether
10 there exists a possibility that immediate execution of a
particular hard deadline asynchronous process may cause
the execution of the asynchronous process, or the
execution of some other asynchronous process, to extend
beyond the beginning of the time slot of the periodic
15 process in the pre-run-time schedule, even if the
periodic process is not ready for execution of said any
predetermined time, and

(b) delaying execution of the hard deadline
asynchronous process if said possibility is found to
20 exist, even if said possibility is the only reason for
delaying the execution of said asynchronous process at
said any time, and even if the delay will cause the
processor to be in an idle state for a time interval of
non-zero length beginning from said any time.

25

30. A method as defined in claim 27, including
carrying out the method on a plurality of processors.

31. A method as defined in claim 29, including
30 carrying out the method on a plurality of processors.

32. A method as defined in claim 1, further
comprising, during run-time:

(a) detecting, at any predetermined time, whether
35 there exists a possibility that immediate execution of a

(b) delaying execution of the first hard deadline asynchronous process if said possibility is found to exist, even if said possibility is the only reason for delaying the execution of the first asynchronous process
5 at said any predetermined time, and even if the delay will cause the processor to be in an idle state for a time interval of non-zero length beginning from said any predetermined time.

10 35. A method as defined in claim 34 including carrying out the method on a plurality of processors.

36. A method as defined in claim 1 comprising during run-time, detecting at least one event of, at any
15 point in time, whether some asynchronous process has arrived by said point in time, if some asynchronous process or periodic process has completed its computation at said point in time, and if said point in time is both the release time and beginning time of a
20 time slot in the pre-run-time schedule for some periodic process, and activating a run-time scheduler at said point in time, and should said at least one event have occurred, determining whether each asynchronous process that has arrived but has not yet been completed should
25 be delayed or immediately put into execution, and at least one of the further steps:

(a) delaying execution of a hard deadline first asynchronous process when the execution of some other hard deadline asynchronous or periodic process which
30 excludes the first asynchronous process has already started by has not yet been completed,

(b) delaying execution of a hard deadline first asynchronous process when execution of some other hard deadline asynchronous or periodic process which has less
35 or equal latitude compared with the latitude of the

first asynchronous process in meeting their respective deadlines has already started but has not yet been completed,

(c) delaying execution of a hard deadline first asynchronous process when execution of some other hard deadline first asynchronous process that excludes a periodic process with less or equal latitude as compared with the latitude of the first asynchronous process in meeting their respective deadlines has already started but has not yet been completed,

(d) delaying execution of a hard deadline asynchronous process in the event there exists the possibility that immediate execution of the latter hard deadline asynchronous process may cause execution of a first periodic process with less or equal latitude to be delayed, when execution of the first periodic process may be preempted by execution of some second periodic process, and the latter hard deadline asynchronous process cannot be preempted by the second periodic process,

(e) delaying execution of a hard deadline asynchronous process when it is not allowed to preempt execution of any first process that excludes some other second hard deadline asynchronous process which has latitude that is less than both said any first process and the latitude of said second asynchronous process, whereby blocking of the second asynchronous process by the duration of more than execution of processes with greater latitude thereof may be avoided,

(f) delaying execution of a hard deadline asynchronous process to allow preemption of execution of the asynchronous process by execution of a first periodic process that has latitude less than or equal to the latitude of the asynchronous process, when the asynchronous process does not exclude the first periodic

process and does not exclude any other asynchronous
process with a latitude that is less than the latitude
of the first periodic process, and there does not exist
execution of some second periodic process that has not
5 been completed such that execution of the second
periodic process is ordered before execution of the
first periodic process and execution of the time slot of
the first periodic process is not nested within the time
slot of the second periodic process in the pre-run-time
10 schedule, and

(g) selecting, among all hard deadline asynchronous
processes that have already arrived and are not yet
completed and are not delayed, a process which has the
least latitude for immediate execution, wherein if more
15 than one process is selected, further selecting a
process among them with a smallest index for immediate
execution.

37. A method as defined in claim 1, comprising
20 during run-time, detecting, in a case in which no hard
deadline asynchronous process or periodic process that
has started is to be immediately put into execution,
conditions of whether there exists an execution of some
first periodic process that is ready for execution and
25 has not completed execution, and there does not exist
any other execution of some second periodic process that
has not yet completed, such that execution of the second
periodic process is ordered before execution of the
first periodic process in the pre-run-time schedule, and
30 the time slot of the first periodic process is not
nested within the time slot of the second periodic
process in the pre-run-time schedule, and there does not
exist any other execution of some third periodic process
that is ready and has not completed execution, such that
35 execution of the third periodic process is nested within

the time slot of the first periodic process in the pre-run-time schedule, and beginning execution of the first periodic process immediately in the event said conditions are true.

5

38. A method as defined in claim 1, comprising during run-time, detecting the conditions in a case in which no hard deadline asynchronous process or periodic process that has started is to be immediately put into
10 execution, whether there exists a soft deadline first asynchronous process with known characteristics that is ready and has not completed execution, and that there does not exist any other second process such that the second process excludes the first process or the first
15 process excludes some third process such that the third process has a latitude that is less than the latitudes of both the first process and the second process, and execution of the second process has started but has not been completed, and in the event the conditions are
20 true, selecting among all such first soft deadline asynchronous processes with known characteristics a process that has the shortest deadline, and in the event among such processes there are some processes that have already started, then selecting a process among them
25 which has already started for immediate execution.

39. A method as defined in claim 1, comprising during run-time, detecting the conditions, in a case in which no hard deadline asynchronous process or periodic
30 process that has started, or periodic process that is ready, or soft deadline asynchronous process with known characteristics that is ready for execution, is to be immediately put into execution, whether there exists a soft deadline first asynchronous process with unknown
35 characteristics that is ready and has not completed

execution, and that there does not exist any other
second process such that the second process excludes the
first process or the first process excludes some third
process such that the third process has a latitude that
5 is less than the latitudes of both the first process and
the second process, and the execution of the second
process has started but has not been completed, and in
the event the conditions are true then selecting among
all such first soft deadline asynchronous processes with
10 unknown characteristics, a process that has the shortest
deadline, and if among such processes there are some
that have already started, then selecting a process
among them that has already started for immediate
execution.

15

40. A method as defined in claim 1, including,
for use in generating the pre-run-time schedule,
determining a worst-case response time of each hard
deadline asynchronous process that has not been
20 converted into a periodic process using a formula
comprising:

the sum of all worst-case computation times of
all asynchronous processes and periodic processes that
have less or equal latitude as compared with the
25 latitude of the asynchronous in meeting their respective
deadlines,

plus the maximum time that the asynchronous
process may possibly be blocked by some asynchronous or
periodic process that has greater latitude as compared
30 with the latitude of the asynchronous process in meeting
their respective deadlines,

plus the worst-case computation time of the
asynchronous process multiplied by the number of
periodic processes with which the asynchronous process
35 has an exclusion relation.

41. A method as defined in claim 1, including, during a pre-run-time phase, determining by simulation a worst-case response time of each hard deadline asynchronous process corresponding to a feasible pre-run-time schedule of periodic processes consisting of an initial part of the pre-run-time schedule and a repeating part of the pre-run-time schedule, wherein for each point in time from zero to the end time of the repeating part of the run-time schedule minus one time unit, simulating execution of the asynchronous process using functions used to determine a run-time schedule and recording response time of the asynchronous process under the assumption that the asynchronous process starts at a point in time under consideration, all other asynchronous processes that can possibly block the asynchronous process arriving at one time unit prior to the point in time under consideration, and all asynchronous processes that have deadlines that are shorter than the deadline of the asynchronous process arriving at the same said point of time under consideration, scheduling executions of periodic processes to start at the beginning time and to complete execution at the end time of their respective time slots in the pre-run-time schedule, wherein whenever the asynchronous process is delayed because it may block execution of some periodic process having less latitude than the latitude of the asynchronous process, or may block execution of some second asynchronous process for the duration of more than one execution of processes having greater latitude as compared with the latitude of the second asynchronous process, all asynchronous processes having less latitude as compared with the latitude of the asynchronous process is delayed in order to delay the asynchronous process for a maximum possible

amount of time, thus simulating all possible worst-case scenarios of executions of the asynchronous process.

42. A method as defined in claim 1, including,
5 during a pre-run-time phase, restricting every periodic process to be executed strictly within its time slot in the pre-run-time schedule by changing release time of execution of each periodic process to be equal to the beginning time of the time slot reserved for execution
10 of the periodic process.

43. A method as defined in claim 1, including,
during a pre-run-time phase, generating tables of safe start time intervals for the executions of hard deadline
15 asynchronous processes, wherein every periodic process is scheduled to be executed strictly within its time slot in the pre-run-time schedule, by changing the release time of execution of each periodic process to be equal to the beginning time of the time slot reserved
20 for execution of the periodic process, wherein for every point in time of the pre-run-time schedule, it is determined whether each asynchronous process should be delayed, under the assumption that the actual start time of execution of every periodic process is equal to the
25 beginning time of its time slot, and the actual end time of execution of every periodic process is equal to the end time of its time slot, wherein for every point in time of the pre-run-time schedule, in the event the hard deadline asynchronous process is to be delayed according
30 the assumptions, the point in time is set to be unsafe and recorded in a corresponding entry in the table for the point in time and the asynchronous process.

44. A method as defined in claim 1, including,
35 during a pre-run-time phase, determining a worst-case

response time of each soft deadline asynchronous process
for which worst-case computation time, deadline and
minimum time between two requests are known before run-
time and that has not been converted into a periodic
5 process, using a formula:

the sum of all worst-case computation times of
all asynchronous processes that have less or equal
latitude as compared with the latitude of the
asynchronous process in meeting their respective
10 deadlines,

plus the sum of all worst-case computation times
of all periodic processes,

plus the maximum time that the asynchronous
process may possibly be blocked by some asynchronous
15 process that has greater latitude as compared with the
latitude of the asynchronous process in meeting their
respective deadlines.

45. A method as defined in claim 1, including,
20 during a pre-run-time phase, determining by simulation a
worst-case response time of each soft deadline
asynchronous process for which the worst-case
computation time, deadline, and minimum time between two
requests are known before run-time, corresponding to a
25 feasible pre-run-time schedule of periodic processes
consisting of an initial part of the pre-run-time
schedule and a repeating part of the pre-run-time
schedule, wherein for each point in time from zero to an
end time of the repeating part of the pre-run-time
30 schedule minus one time unit, and simulating the
execution of the asynchronous process using functions
which are used in determining a run-time schedule and
recording the response time of the asynchronous process
under the assumption that the asynchronous process
35 starts at the point in time and that all other soft

deadline asynchronous processes that can possibly block
the asynchronous process arrive at one time unit prior
to the point in time, and all soft deadline asynchronous
processes that have deadlines which are shorter than the
5 deadline of the asynchronous process and all hard
deadline asynchronous processes arrive at the same point
in time, all executions of periodic processes starting
at the beginning time and completing at the end time of
their respective time slots in the pre-run-time
10 schedule, thus simulating all possible worst-case
scenarios of executions of the asynchronous process.

46. A method as defined in claim 1, including,
during a pre-run-time phase, generating tables of safe
15 start time intervals for the executions of hard deadline
asynchronous processes, wherein every periodic process
is scheduled to be executed strictly within its time
slot in the pre-run-time schedule, by changing the
release time of execution of each periodic process to be
20 equal to the beginning time of the time slot reserved
for execution of the periodic process, wherein for
selected points in time of the pre-run-time schedule, it
is determined whether each asynchronous process should
be delayed, under the assumption that the actual start
25 time of execution of every periodic process is equal to
the beginning time of its time slot, and the actual end
time of execution of every periodic process is equal to
the end time of its time slot, wherein for selected
points in time of the pre-run-time schedule, in the
30 event the hard deadline asynchronous process is to be
delayed according the assumptions, that point in time is
set to be unsafe and recorded in a corresponding entry
in the table for the point in time and the asynchronous
process.

35

47. A method as defined in claim 46, in which the selected points in time are every point in time.

48. A method as defined in claim 1, including,
5 during a pre-run-time phase, determining by simulation a worst-case response time of each soft deadline asynchronous process for which the worst-case computation time, deadline, and minimum time between two requests are known before run-time, corresponding to a
10 feasible pre-run-time schedule of periodic processes consisting of an initial part of the pre-run-time schedule and a repeating part of the pre-run-time schedule, wherein for selected points in time from zero to an end time of the repeating part of the pre-run-time
15 schedule minus one time unit, simulating the execution of the asynchronous process using functions which are used in determining a run-time schedule and recording the response time of the asynchronous process under the assumption that the asynchronous process starts at the
20 selected point in time and that all other soft deadline asynchronous processes that can possibly block the asynchronous process arrive at one time unit prior to the selected point in time, and all soft deadline asynchronous processes that have deadlines which are
25 shorter than the deadline of the asynchronous process and all hard deadline asynchronous processes arrive at the same point in time, all executions of periodic processes starting at the beginning time and completing at the end time of their respective time slots in the
30 pre-run-time schedule, thus simulating all possible worst-case scenarios of executions of the asynchronous process.

49. A method as defined in claim 48, in which
35 the selected points in time are every point in time.

50. A method of processing a plurality of processes, some of which are periodic and some of which are asynchronous, comprising:

- 5 (i) prior to executing the processes on a processor:
- (a) determining which asynchronous processes have less flexibility in meeting their deadlines than any of the periodic processes,
 - (b) adding the execution time of each of the
- 10 less flexible asynchronous processes to the execution time of each of the periodic periodic processes,
- (c) scheduling each of the periodic processes into time slots,
- (ii) and during run-time of the processor:
- 15 (d) executing the periodic processes according to the schedule, interrupting any periodic process to execute an of said less flexible asynchronous processes for which a request to execute has been received by the processor,
- 20 (e) on receiving a request to execute an asynchronous process which has greater or equal flexibility in meeting their deadlines than any of the periodic processes, scheduling the requesting asynchronous process at a time which will not conflict
- 25 with execution and completion of any of the periodic processes, and
- (f) execute the scheduled latter asynchronous process at its scheduled time.

- 30 51. A method as defined in claim 50, including the step of converting at least one asynchronous process to a new periodic process prior to step (i)(a) in the event that a ratio of processor capacity which needs to be reserved for executing the new periodic process, to
- 35 the processor capacity which needs to be reserved for

the asynchronous process if unconverted, exceeds a predetermined value, and the step of otherwise treating each new periodic process in a similar manner to other periodic processes.

5

52. A method of processing a plurality of processes, some of which are periodic and some of which are asynchronous, comprising:

(i) prior to executing the processes on a processor:

10 (a) determining which asynchronous processes have less flexibility in meeting their deadlines than any of the periodic processes,

(b) adding the execution time of each of the less flexible asynchronous processes to the execution
15 time of each of the periodic processes,

(c) scheduling each of the periodic processes into time slots,

(d) converting each asynchronous process which has greater or equal flexibility in meeting their
20 deadlines than any of the periodic processes into a new periodic process, and scheduling the new periodic process at a time which will not conflict with execution and completion of any of the other periodic processes,
(ii) and during run-time,

25 (e) executing the periodic and new periodic processes, interrupting any of the periodic and new periodic processes to processes any of the less flexible asynchronous processes for which a request to execute may be received at any time.

30

53. A method as defined in claim 52, including the step of converting at least one asynchronous process to a new periodic process prior to step (i)(a) in the event that a ratio of processor capacity which needs to
35 be reserved for executing the new periodic process, to

the processor capacity which needs to be reserved for the asynchronous process if unconverted, exceeds a predetermined value, and the step of otherwise treating each new periodic process in a similar manner to other
5 periodic processes.

54. A method as defined in claim 50, including adding the execution time of each of the less flexible asynchronous processes to the execution time of each of
10 the periodic processes which has greater or equal flexibility in meeting their deadlines than any of the periodic processes, interrupting the scheduled latter asynchronous process to process any of the less flexible asynchronous processes for which a request to execute
15 may be received at any time.

55. A method as defined in claim 51, including adding the execution time of each of the less flexible asynchronous processes to the execution time of each of
20 the periodic processes which has greater or equal flexibility in meeting their deadlines than any of the periodic processes, interrupting the scheduled latter asynchronous process to process any of the less flexible asynchronous processes for which a request to execute
25 may be received at any time.

56. A method of scheduling execution of processes by a processor comprising:
(a) scheduling periodic time slots for all periodic
30 processes which time slots each include time for each of the periodic processes and time for all asynchronous processes which have less flexibility in meeting their deadlines than do the periodic processes,
(b) determining worst case response times of all
35 other processes,

(ii) reserving processor capacity for
ahka processes by adding computation time of each ahka
process to computation time of every periodic process
that has greater flexibility in meeting its deadline
5 than of the ahka process, thereby to allow each ahka
process to preempt execution of any such periodic
process which has the greater flexibility if possible at
the run-time,

II.1. determining the schedulability of all phk
10 processes having known characteristics and new periodic
processes converted from ahkp processes,

2. constructing a pre-run-time schedule in
which one or more time slots are reserved for execution
of every phk process and every new periodic process
15 converted from one ahkp process, wherein a time slot
reserved for a phk process includes time reserved for
execution of all ahka processes that have less
flexibility in meeting their deadlines than the phk
process,

20 3. adjusting the lengths of time slot periods
by predetermined parameters for controlling balance
between a utilization level and length of a pre-run-time
schedule,

III.1. determining worst case response times of
25 all ahka processes,

2. verifying schedulability of each ahka
process by checking whether its deadline is greater or
equal to its worst-case response time,

IV. 1. determining the schedulability of all psk
30 processes, while maintaining the previously determined
schedulability of all phk and ahka processes,

2. reconstructing a pre-run-time schedule in
which one or more time slots are reserved for execution
of every phk process including every new phk process
35 converted from an ahka process, for every psk process,

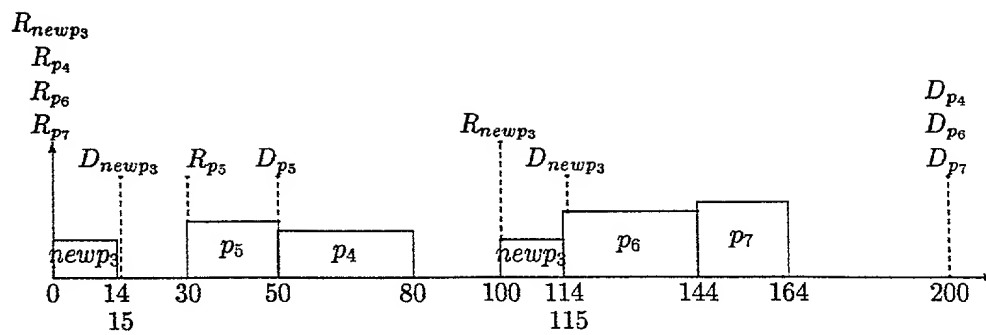


FIG. 1

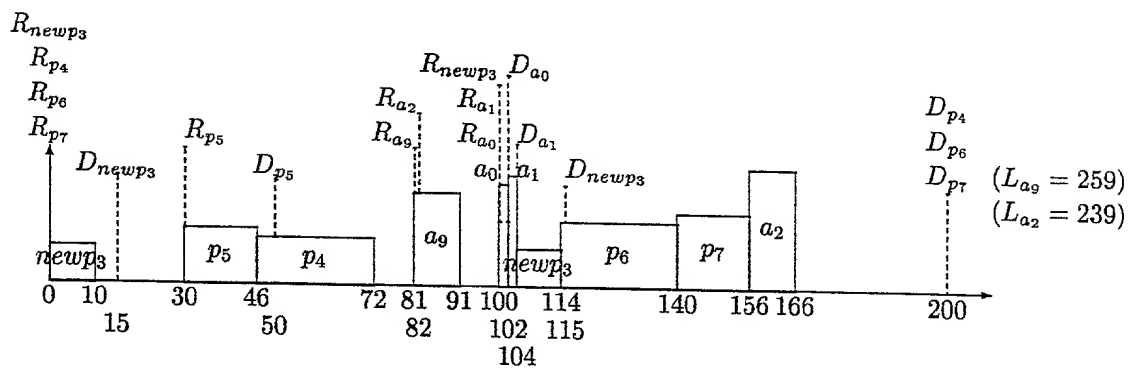


FIG. 2

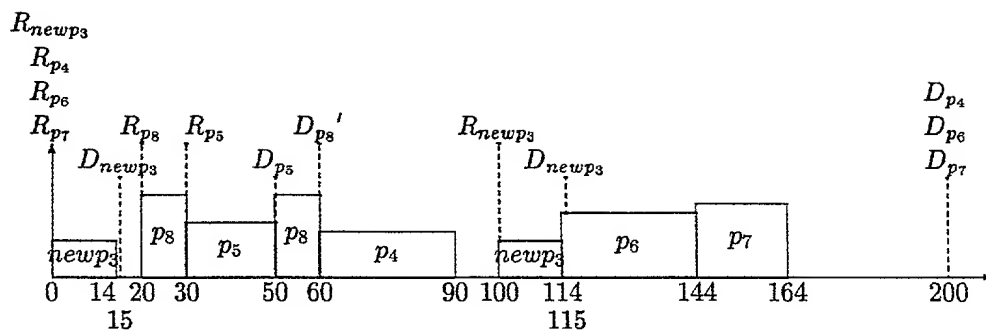


FIG. 3

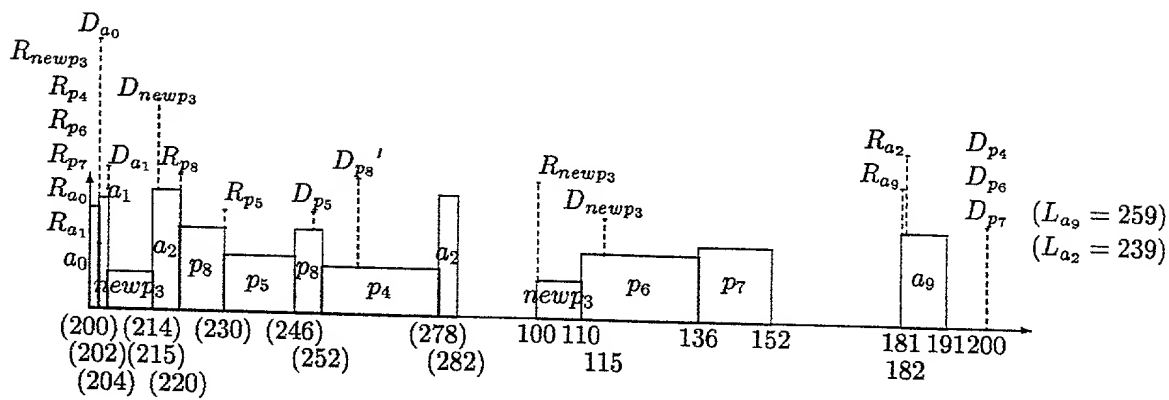


FIG. 4

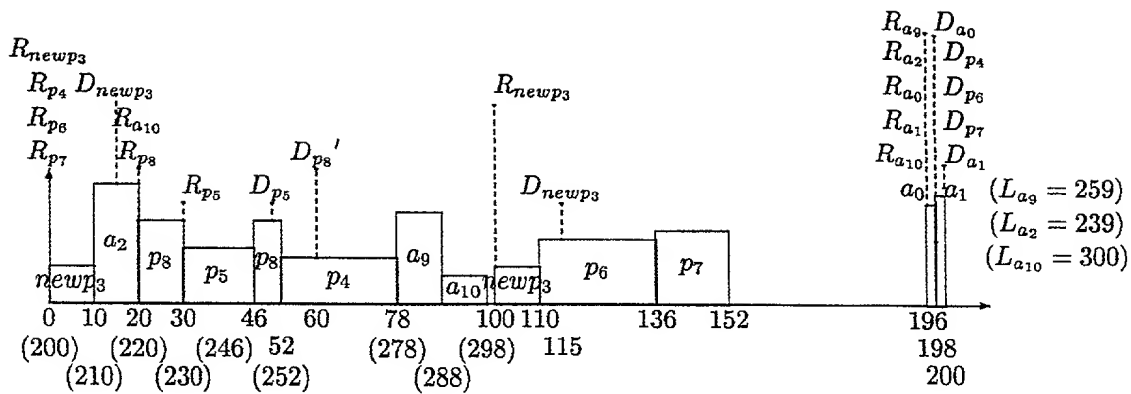


FIG. 5

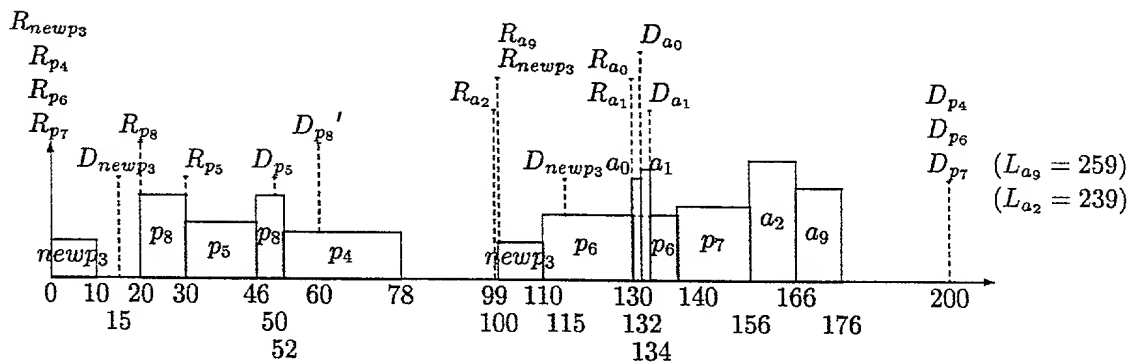


FIG. 6

FIG 9

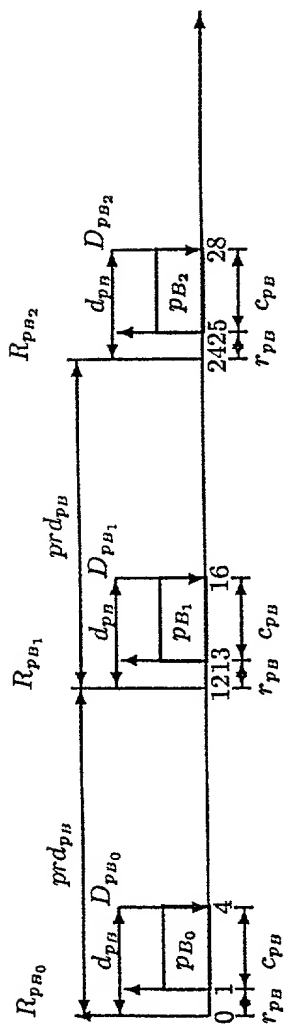
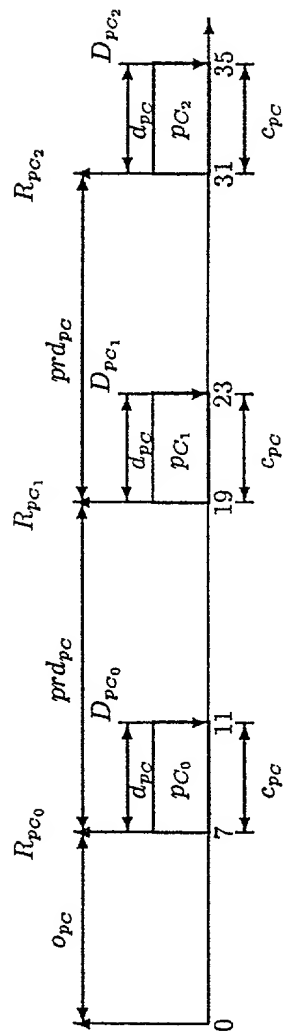


FIG 11



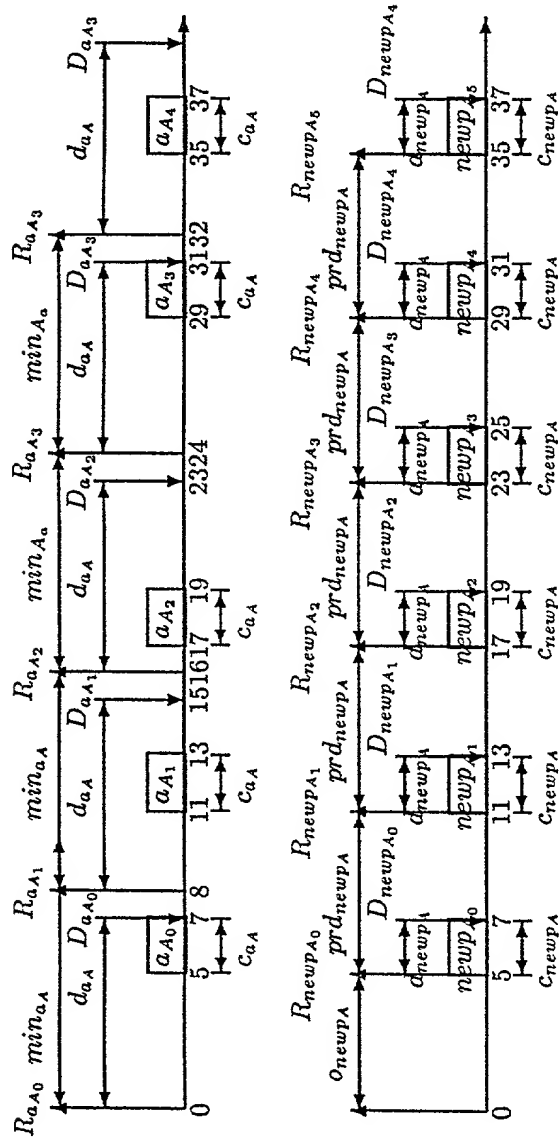


FIG. 13

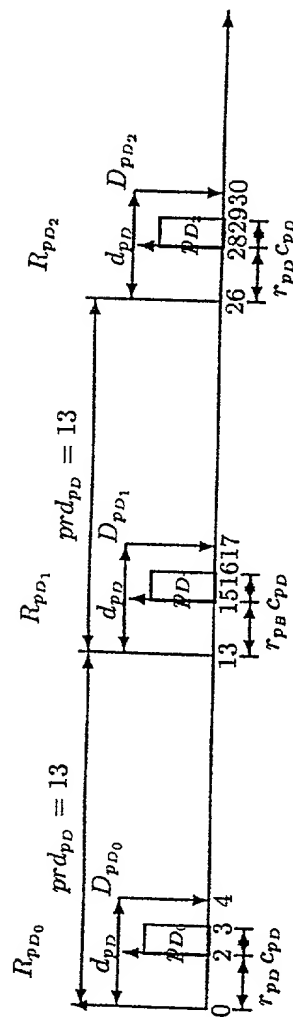


FIG. 15

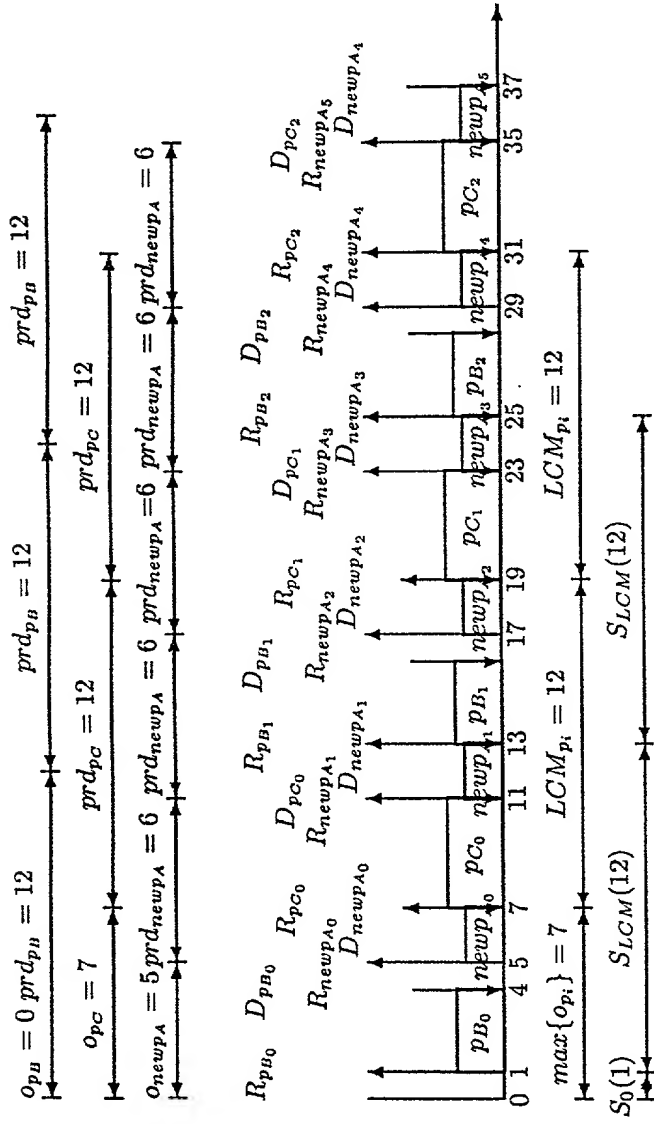


FIG. 14

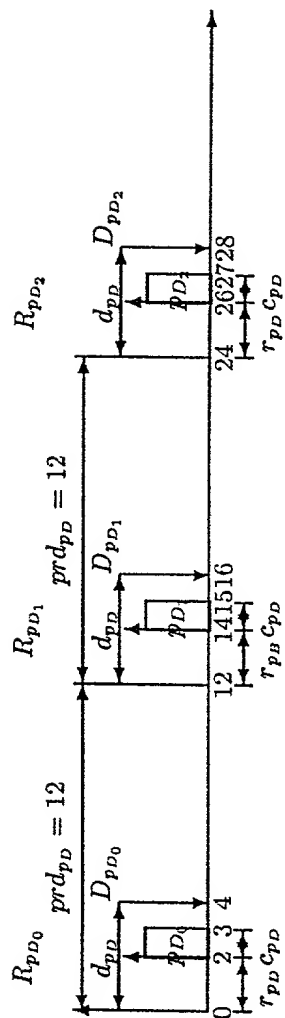


FIG. 16

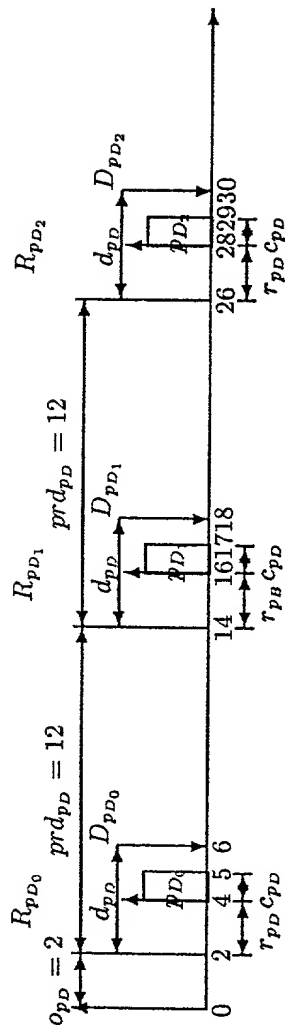


FIG. 17

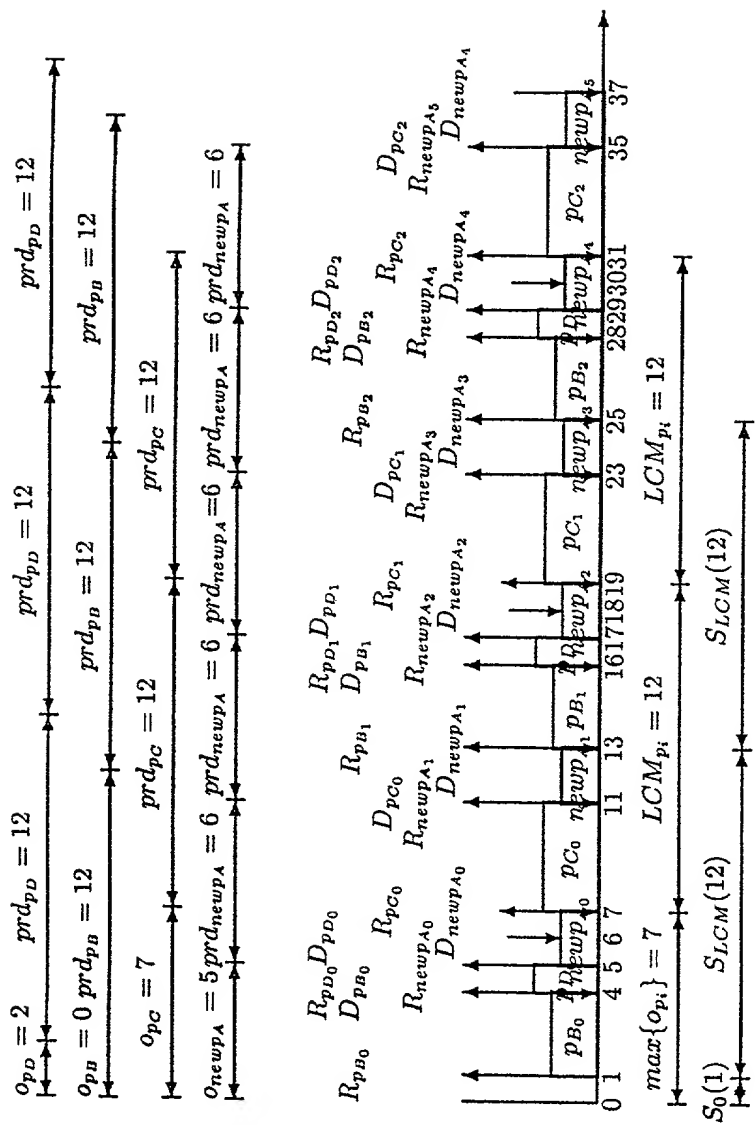


FIG. 18

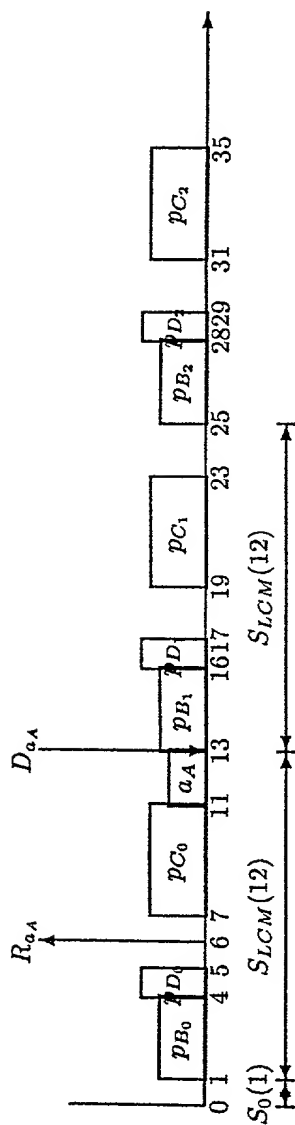


FIG. 19

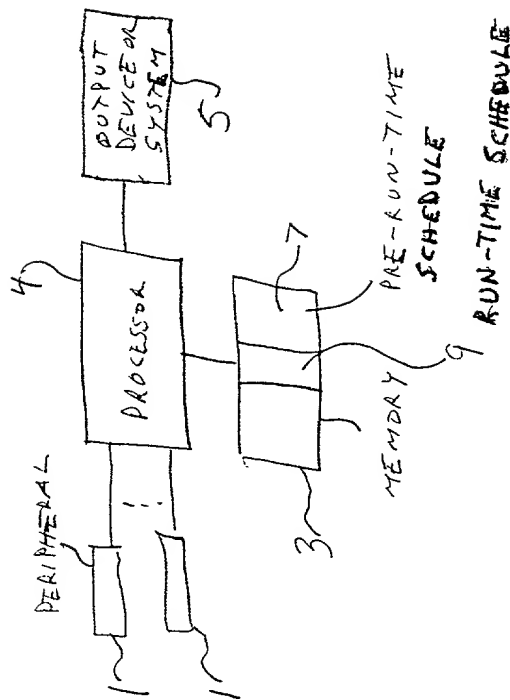


FIG. 24

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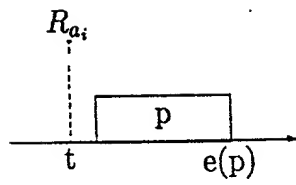


FIG 20A

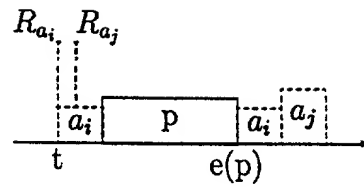


FIG 20B

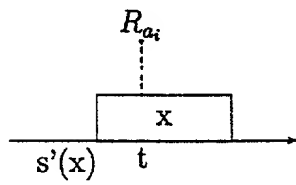


FIG. 20C

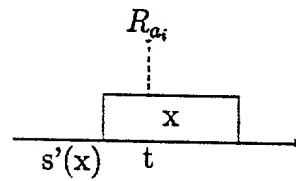


FIG. 20D

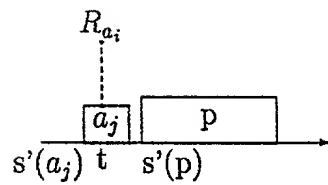


FIG. 20E

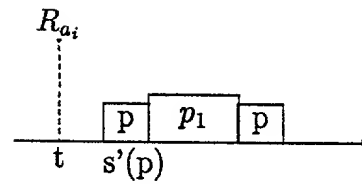


FIG. 20F

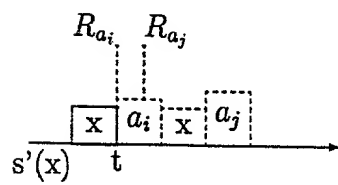


FIG. 20G

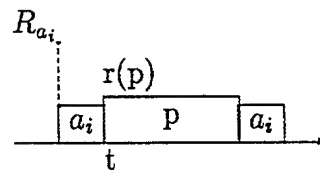
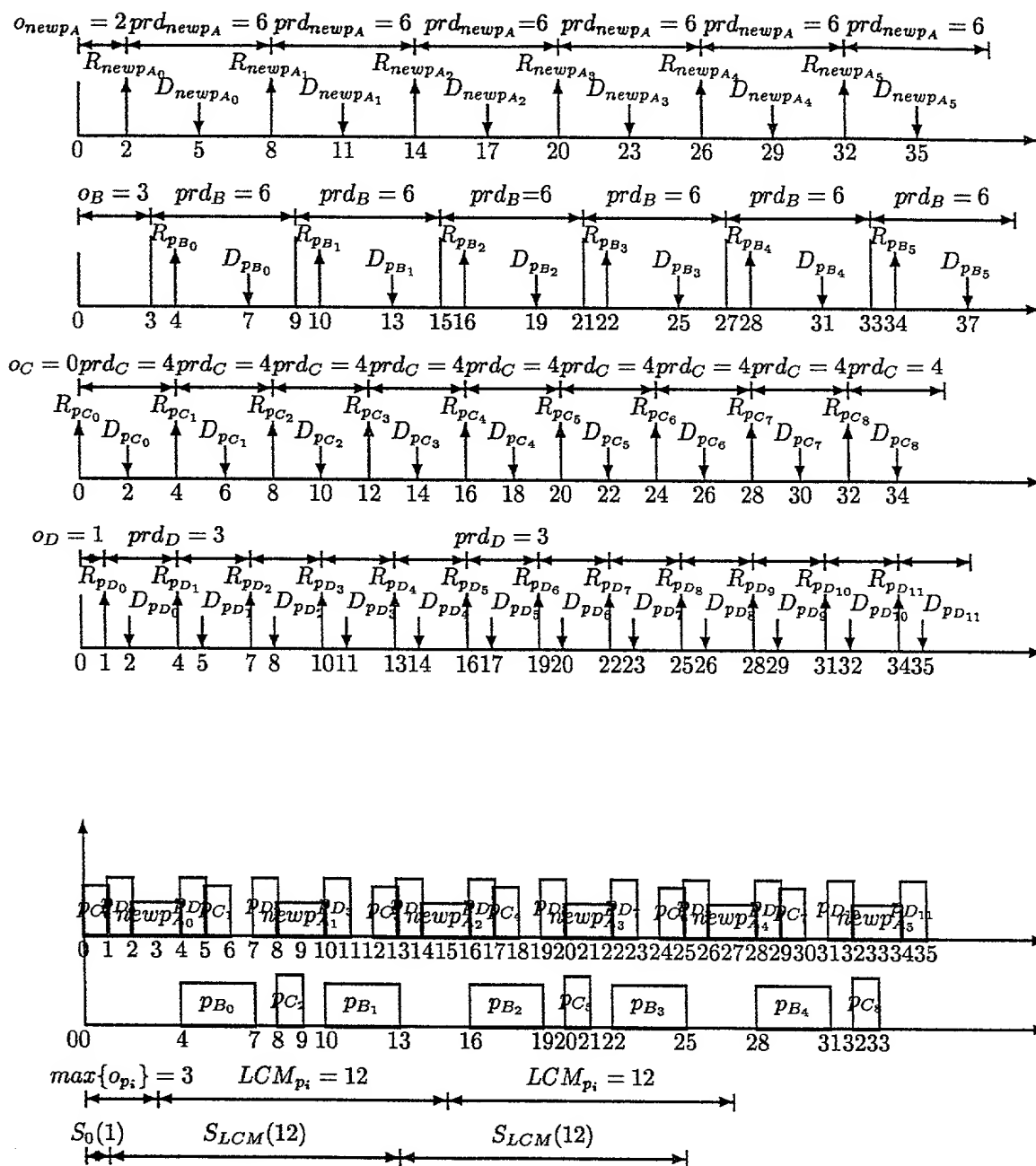


FIG. 20H



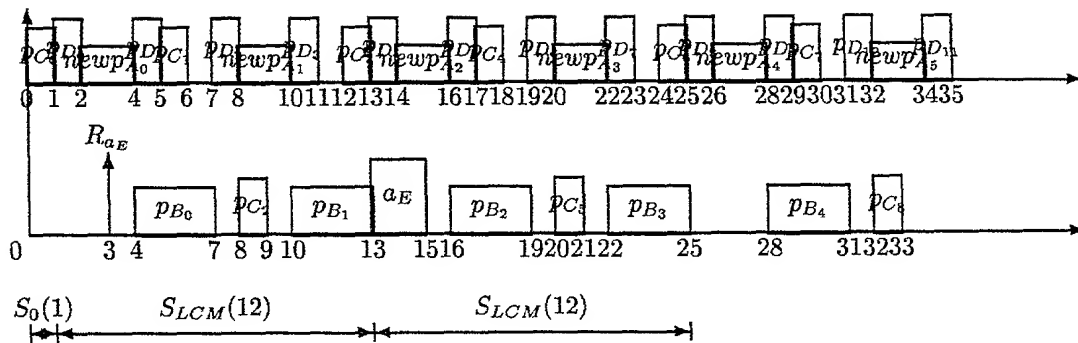


FIG. 22

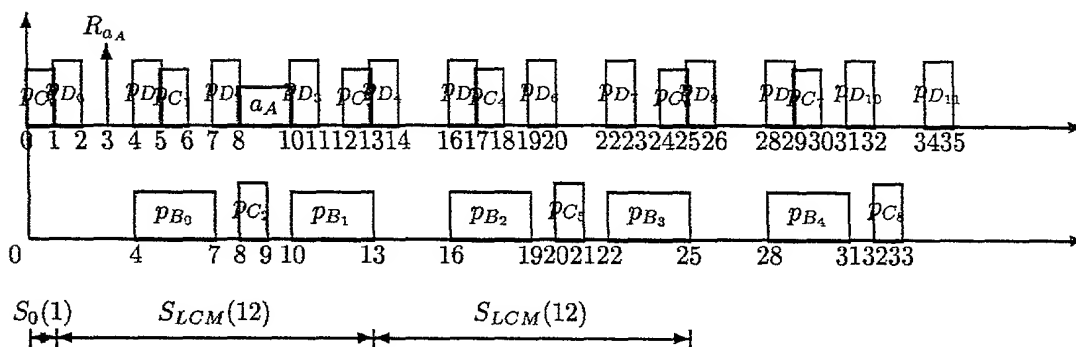


Fig. 23

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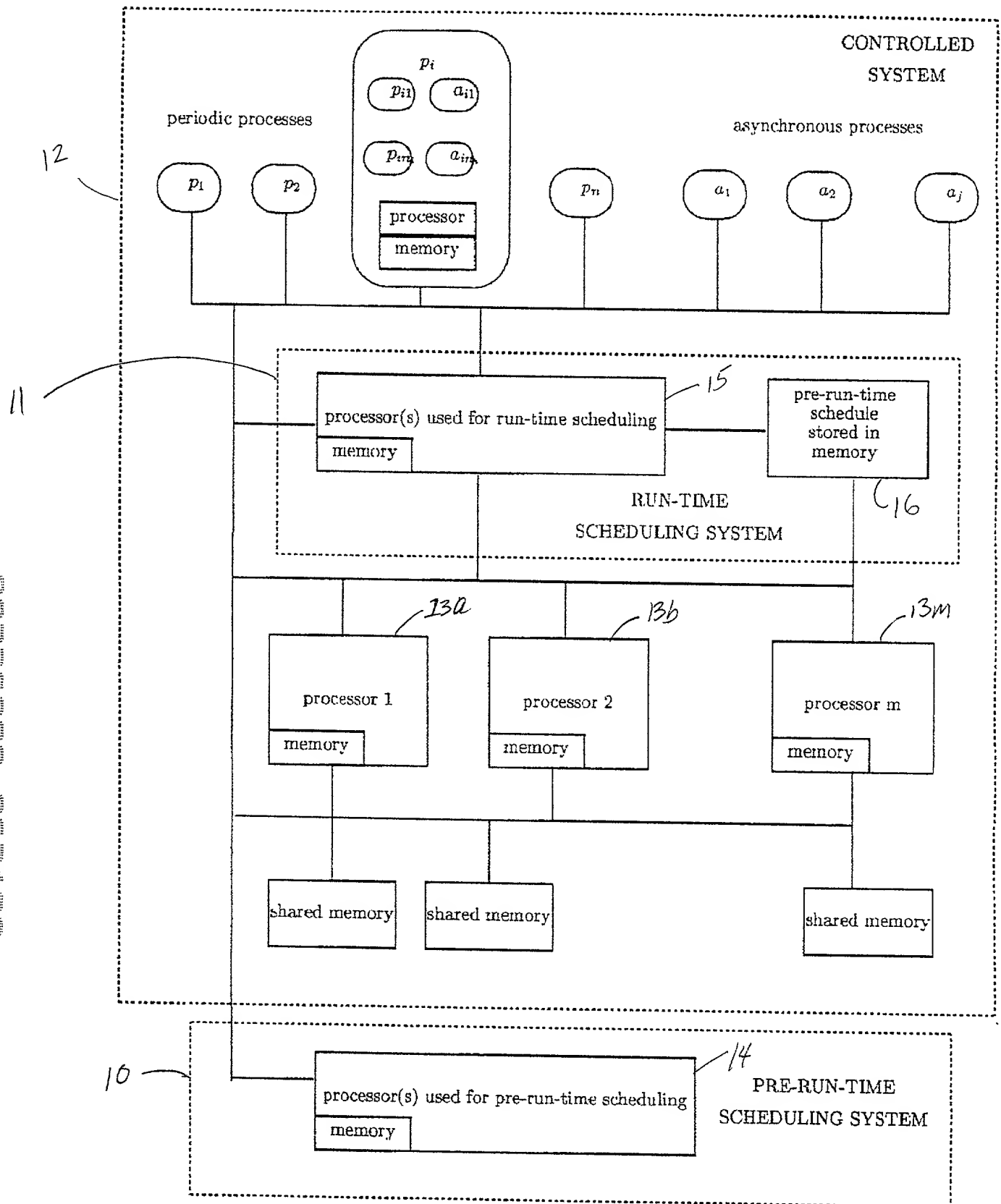


FIG 24A

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled **A METHOD OF SCHEDULING EXECUTIONS OF PERIODIC AND ASYNCHRONOUS REAL-TIME PROCESSES HAVING HARD OR SOFT DEADLINES**

the specification of which is attached hereto unless the following is checked:

___ was filed on _____ as United States
Application No. _____ ; or
___ PCT International Application No. _____
___ and was amended on _____ (if applicable)

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, §119 (a) - (d) or §365(b) of any foreign application(s) for patent or inventor's certificate, or §365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)

Priority Claimed

(Number)	(Country)	(Day/Month/Year Filed)	Yes	No
____	____	____	____	____
____	____	____	____	____
____	____	____	____	____

I hereby claim the benefit under Title 35, United States Code, §119(e) of any United States provisional application(s) listed below:

Application Serial No. _____	(Filing Date) _____
Application Serial No. _____	(Filing Date) _____

I hereby claim the benefit under Title 35, United States Code §120 of any United States application(s), or §365(c) of any PCT International application, designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application:

(Appln. No.)	(Filing Date)	(Status) (patented, pending, abandoned)
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(Appln. No.)	(Filing Date)	(Status) (patented, pending, abandoned)
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As a named inventor(s), I(we) hereby appoint the following attorney(s) and/or agent to prosecute this application and transact all business in the Patent and Trade Mark Office connected therewith:

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I hereby declare that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true; and further, that these statements were made with the knowledge that willful false statements, and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full Name of sole or first inventor
Jia XU

Date

June 14, 1999 X

Inventor's signature

 X

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